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Wright-Patterson Air Force Base, Ohio

AN INVESTIGATION OF THE RELATIONSHIP OF SECTION PRODUCTION COSTS TO TOTAL PRODUCTION COSTS OF GAS TURBINE ENGINES

James K. Greene, Captain, USAF
Arthur E. Stark, Captain, USAF

LSSR 34-77A

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The Air Force Aero Propulsion Laboratory is currently exploring techniques which may be used to estimate the production costs of gas turbine engines in the conceptual and validation phases of system acquisition. This study served as a part of that on-going exploration and was designed to investigate the relationship of engine section production costs to total production costs of gas turbine engines. The results of this research include the following findings: (1) correlation analysis provides an effective technique for determining those relationships; (2) among engine sections, costs of the high pressure turbine and compressor sections demonstrated the highest consistent correlations with total engine production cost; (3) regression analysis using the costs of high pressure turbine and compressor sections appears to hold promise for estimating total engine production cost; (4) a modification of the industrial engineering approach in which a cost estimate of the high pressure turbine section would be "built up" and used, in turn, to estimate production costs of the complete engine also appears to hold promise; and (5) engine cost data presently collected and retained within the Air Force appear inadequate for estimating studies utilizing the production costs of engine parts, assemblies, and sections.

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AN INVESTIGATION OF THE RELATIONSHIP OF SECTION PRODUCTION COSTS TO TOTAL PRODUCTION COSTS OF GAS TURBINE ENGINES

A Thesis
Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Logistics Management

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has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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INTRODUCTION

Problem Statement

Office of Management and Budget (OMB) Circular No. A-109, dated April 5, 1976, established policies to be followed by executive branch agencies in the acquisition of major systems (13:1). In accordance with these policies, the Air Force Aero Propulsion Laboratory (AFAPL) is required to estimate jet engine production costs from the conceptual through the production phase of weapons system development. The AFAPL has recognized that existing cost estimating techniques are inadequate for this purpose (24).

The AFAPL needs a cost estimating technique which estimates the impact of engine design changes on total engine production costs (2,24). As a prerequisite to developing such techniques, an understanding of the sensitivity of production costs to design changes of engine sections is needed.

Background and Justification

Life Cycle Cost (LCC) is defined by Air Force Regulation 800-11 as the total cost of an item or system over its full life (32). Figure 1 illustrates the phases in a weapon system life cycle. LCC, as applied to gas turbine

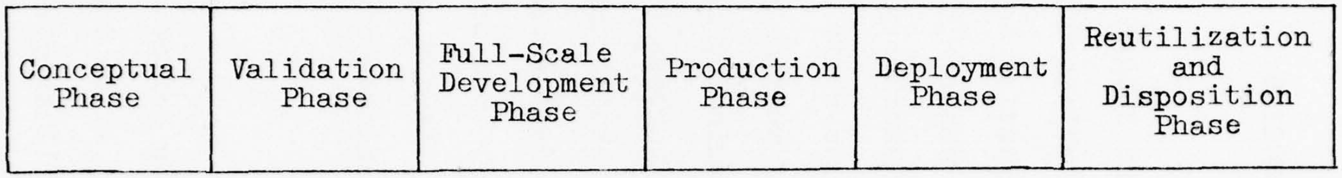

Figure 1

Life Cycle of a Major Weapon System (33:2-2) engines, includes costs to develop and test the engine through the full-scale development phase, costs to produce the engine in quantity during the production phase, and costs to support the engine from the deployment phase through retirement from the inventory (disposition phase) (25:156-7).

The AFAPL can play a vital part in reducing the LCC of an engine (25:157). Most of the decisions which affect LCC are made very early in the weapons acquisition process. It is during this advanced conceptual phase that the laboratory has the opportunity to provide the advanced design technologies which form the future technological base for an engine (25:157).

Better cost estimating techniques, sensitive to design changes, are needed (25:158). These improved techniques are needed so that the AFAPL can consider cost trade-offs inherent in design factors such as energy output, efficiency, and manufacturing methods in establishing engine configuration (25:158).

Previous investigation by AFAPL into various cost estimating methods and models has identified two general approaches to developing cost estimating techniques for jet engines (3). The first cost estimating technique is the "parametric" approach. The term "parametric" is used because the technique employs variables which explain the characteristics (or parameters) of the engine such as performance (e.g., thrust-to-weight ratio, turbine-inlet-temperature), physical (e.g., weight, airflow), and characteristics related to the development process (e.g., complexity, materials index) (3:2). Statistical regression analysis is often used to derive a relationship between one or more engine "parameters" and cost (3:2).

The second major cost estimating technique is termed "the industrial engineering approach." This technique entails the examination of work at a low level, with detailed estimates of the cost elements required to produce each engine part. These estimates are then aggregated to sub-assemblies and higher assemblies until the entire engine is "built" into a total cost estimate (3:3).

Major drawbacks have been identified for both of these cost estimating techniques. A deficiency in the parametric technique is that cost estimating relationships are developed based upon the historical data from previous engines and may not be predictive of new engines (25:158). The deficiencies with the industrial engineering approach are not attributed to the validity of the technique itself. Rather, they lie in the government's lack of detailed manufacturing data and the shortage of resources needed to apply the technique (3:3). In 1971, Dr. Bruce N. Baker surveyed over 600 individuals within the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) cost estimating and analysis organizations (1:38). The majority of these individuals recognized the deficiencies in application of the industrial engineering approach. However, they voiced preference for this approach over the parametric approach if the deficiencies could be overcome (1:52-9).

In an effort to create the requisite methodology to establish a credible engine acquisition costing model, the AFAPL, in 1974, initiated a Senior Investigator Program with both Purdue University and Georgia Institute of Technology to evaluate cost estimating approaches in industry (3:25).

Deutsch and Berry in a Georgia Institute of Technology report described the state-of-the-art of methodological approaches to life cycle costing contained in technical literature and employed in selected industrial sectors (9:ii). They concluded that the difference between the parametric and engineering approaches was only in terms of the level of system description. The report asserted that:

> . . . the problems of estimating costs for individual component parts in the 'engineering' approach are identical to the problems inherent in the estimation of their assembly in a single pass [9:34].

Given the choice between the parametric and industrial engineering approaches, Deutsch and Berry voiced strong preference for the latter, although they asserted that " . . . both approaches to cost estimation are overly dependent on a cost model [9:34]." Regression models in the parametric approach utilize proxy variables such as those which describe engine performance (9:34). In the engineering approach, estimated parts costs must be aggregated into a total engine cost estimate which treats parts costs as additive, or allows for some decreasing cost synergy when parts, assemblies, and sections are aggregated to the complete engine, or some combination of the two (9:34-5). They concluded by stating that a manufacturing line simulation model offered a possible alternative approach to a cost model reflecting the manufacturing environment (9:35).

The purpose of the Purdue University study was:

> . . . to survey the state of the art and the actual practice of production cost estimation of proposed new turbine engines to determine the feasibility of the Wright-Patterson Air Force Aero Propulsion Laboratories having their own capability of predicting production costs . . . for both newly developed engine designs and also changes to all types of engines, new or old [11:3].

The Purdue University study by Drake, Reda, and Allen resulted in two major conclusions.

The first conclusion was that the industrial engineering approach was feasible for AFAPL. The Purdue researchers based this conclusion on findings of their study of manufacturing techniques and factory costing procedures of two turbine engine manufacturers (11:5). However, AFAPL would encounter major problems because " . . . they do not have the data base created by past manufactured products and they do not have daily contact with the shop floor [11:19]." In addition, Drake, Reda, and Allen felt that to plan and execute a complete cost estimating system using the industrial engineering approach would require three to five personnel with skills in the following areas (11:29):

1. Industrial Engineering--Manufacturing technology.

2. Materials Sciences--Metals and ceramics, especially high temperature.

3. Computer Applications--Data base design, list processing languages, time sharing systems.

4. Economics--Forecasting, metals, and manufacturing industries' price trends.

5. Business--Cost accounting, standard cost systems.

Drake, Reda, and Allen's second conclusion was that use of regression analysis, as is done in the parametric approach, could be extended to engine components and subcomponents or parts (12:23). They asserted that difficulties would be encountered at the section level[1] because " . . . all engines are not simply scale ups or scale downs of a single basic design . . . [12:22]." However, they felt that these difficulties could be overcome by proceeding to a lower level (i.e., assemblies or parts) with regression analysis because engines which are " . . . different at the component level all tend to have disks, blades, vanes, etc. [12:24]."

A third research effort sponsored by AFAPL, conducted by Mullineaux and Yanke of the School of Systems and Logistics, Air Force Institute of Technology, was completed in June 1976. A proposed methodology for estimating engine costs was developed which built upon parametric models developed by the RAND Corporation and currently used by the Air Force. These parametric models were modified by adding material factor variables developed by the Navy. The Navy had developed material factors based on the following theory:

> . . . that advanced engine technology and the increasing use of super alloys in jet engines are closely correlated. If the theory was true then engine costs could be predicted using a CER [Cost Estimating Relationship] containing a materials

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[1] For definitional breakdown of engine, sections, assemblies, and parts, see Appendix A.

> factor. This factor would automatically update the cost-estimating model as changes in technology occurred [21:21].

Mullineaux and Yanke found the RAND models currently in use by the Air Force required statistical verification to be operationally effective (i.e., the models should incorporate confidence interval testing at a specified alpha level for each prediction) (21:74). They also asserted that "materials-related variables should be included as prime candidates for independent variables in future cost estimating models for jet engines [21:80]."

Added impetus was given to the AFAPL's efforts to create a credible acquisition costing model by the direction contained in OMB Circular No. A-109, dated April 5, 1976 (13). The circular established major system acquisition policies for application by Federal agencies. Among the major system acquisition management objectives set forth, the following has particular applicability to the activities of AFAPL:

> Maintain a capability to: Estimate . . . costs for system development, engineering, design, demonstration, test, production, operation and support. . . . Estimate . . . costs during system design concept evaluation . . . to ensure appropriate tradeoffs among investment costs, ownership costs, schedules, and performance [13:5].

This research effort comprises a portion of an on-going exploration of cost estimating techniques applicable to jet engines sponsored by AFAPL.

Objective

The objective of the research was to determine the relationship of section production costs to total production costs of gas turbine engines. More specifically, the research was aimed at determining what cost correlations might exist between the following:

1. Turbine engine sections,

2. Turbine engine sections and the completed engine.

Research Questions

The researchers proposed to answer the following questions in order to determine what relationships might exist between the production costs of gas turbine engines and turbine engine sections:

1. What is the relationship between engine section production costs and total engine production costs?

2. What are the relationships between the production costs of engine sections?

3. Do these cost relationships provide insight into techniques which could be used for predicting production costs and design change costs of gas turbine engines?

Chapter 2

RESEARCH METHODOLOGY

Overview

The research methodology was designed to determine the relationships which might exist between the production cost of jet engine sections and the cost of the complete engine. Cost of the complete engine and costs of engine sections were treated as random variables. Correlation analysis was used to identify the relationship of engine section production cost to total engine production cost. Partial correlation was then used to determine the net contribution of particular engine sections to total cost while controlling the effects of other sections. The following topics are covered in this chapter:

1. Variables of interest,
2. Justification for variable selection,
3. Data collection,
4. Data description,
5. Population and sample,
6. Analysis procedures,
7. Criteria tests,
8. Summary list of limitations, and
9. Summary list of assumptions.

Variables of Interest

The variables of interest were production costs of the complete turbine engine and production cost of turbine engine sections. These variables are listed in Table 3. Complete definitions are provided in Appendix A.

Justification for Variable Selection

Two previous studies have identified engine cost breakdowns which support the selection of the variables of interest. Participants in the Air Force/Industry Manufacturing Cost Study held at Sagamore, New York, 28 August - 1 September 1972 provided the engine cost breakdown shown in Table 1 (30:15). At a Joint Air Force/Industry Low Cost Manufacturing/Design Seminar held at French Lick, Indiana, 22-24 May 1973, participants from the Garrett Corporation presented distributions of engine section costs as a percent of total cost (29:597,600). These are shown in Figures 2 and 3. At the same seminar, participants from Pratt and Whitney Aircraft Company provided the breakdown of engine cost shown in Table 2 (29:449). These tables and figures show dissimilar engine breakdowns.

In an effort to define an engine breakdown which could be used to assign costs to the functional sections of gas turbine engines, the researchers sought the advice of Mr. Kenneth Stalker, Chief Consultant, General Electric

Table 1

Engine Cost Breakdown (%)

Engine Component	Large Turbo-Fan	Small Turbo-Shaft	Augmented Turbo-Fan	Large Old Jet	Small Old Jet
Disks & Shafts	16	18	16	12	7
Airfoils	29	17	14	14	10
Frames & Sumps	19	16	16	18	7
Casing & External Hardware	14	7	10	13	7
Combustor	2	3	1	.5	3
Augmentor/Exhaust Nozzle	0	1	19	13	13
Controls & Accessory Drives	7	24	10	17	37
Configuration Hardware	3	4	4	3	6
Assembly and Closure	10	10	10	9.5	10
Totals	100	100	100	100	100

<u>Source:</u>

Air Force/Industry Manufacturing Cost Study (30:15).

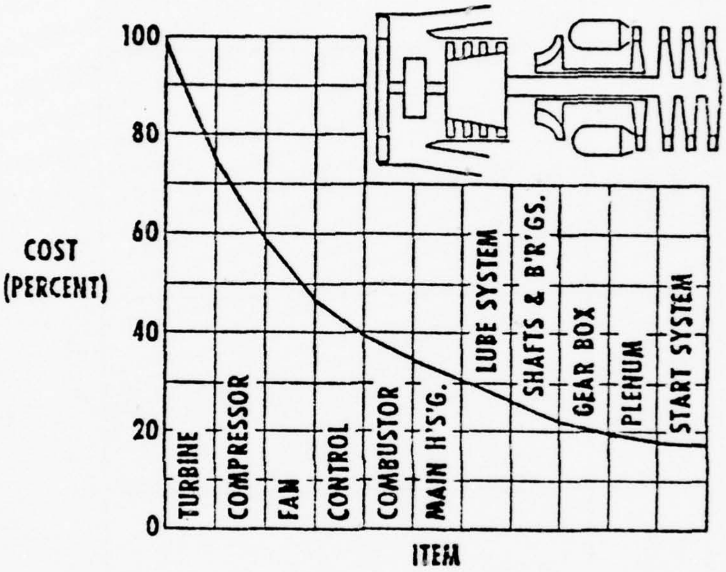


Figure 2

Cost Distribution Curve for a Turbofan Engine

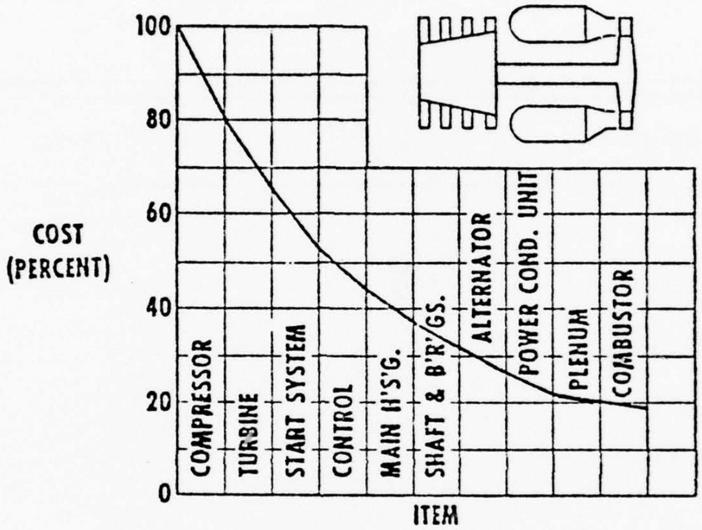


Figure 3

Cost Distribution Curve for a Turbojet Engine

Table 2

Percentage Distribution of Engine Cost

Component	% of Cost
Fan	11
Compressor	14
Combustor	3
Turbine	20
Augmentor	5
Nozzle	12
Brgs-Lube System	5
External Structure	11
Controls	19

Source:

Pratt and Whitney Aircraft Company (29:449).

Laboratories. Mr. Stalker proposed an engine breakdown consisting of ten sections (28). AFAPL recommended that Mr. Stalker's proposed breakdown be modified slightly by treating augmentor and nozzle as a single section. The augmentor and nozzle comprise what is commonly known as the afterburner section (2). The resultant engine breakdown is shown in Table 3. Total engine production cost and production costs of the nine sections shown represent the independent variables for this research.

In summary, based upon the Air Force/Industry Manufacturing Cost Study, the Air Force/Industry Low Cost Design Seminar and the expert opinion referenced above, the variables previously shown in Table 3 were selected as variables of interest for correlation analysis. The sections selected as independent variables are functionally separated, yet when aggregated represent a complete gas turbine engine in physical terms as well as in terms of total production costs (2). A pictorial representation of these variables is shown in Figure 4.

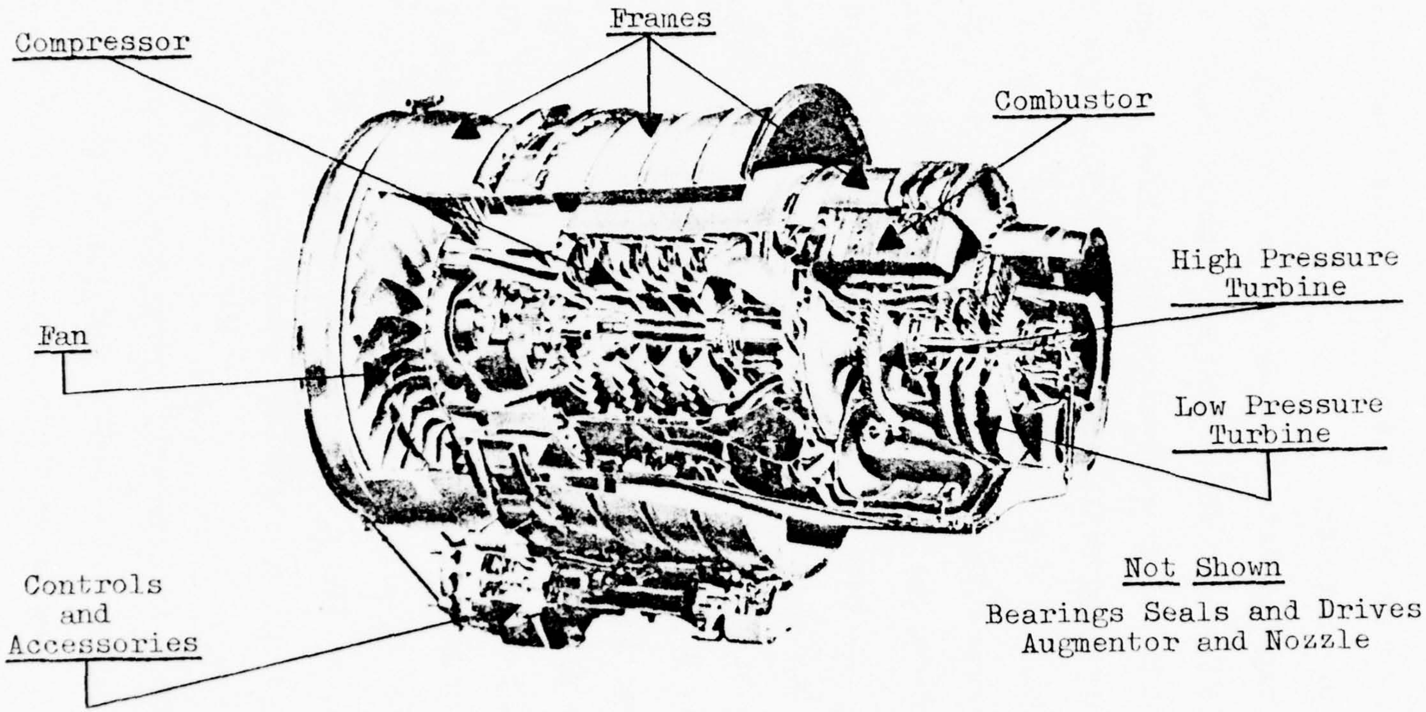
Data Collection

Production cost data for gas turbine engines were required for the proposed analysis. It was necessary to collect production costs for complete engines as well as

Table 3

List of Independent Variables

TCOST = Total Engine Production Cost
X1 = Fan
X2 = Compressor
X3 = Combustor
X4 = High Pressure Turbine
X5 = Low Pressure Turbine
X6 = Bearings, Seals, and Drives
X7 = Controls and Accessories
X8 = Frames
X9 = Augmentor and Nozzle



Not Shown

Bearings Seals and Drives
Augmentor and Nozzle

Figure 4

Engine Section Pictorial Representation (27:596)
(AIRESEARCH TFE731-2 Engine)

production costs for the engine sections identified as variables of interest.

Potential data sources within Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC) were surveyed. Potential sources contacted within the Comptroller, ASD were the Comptroller Cost Library (16), Life Cycle Cost Office (15), and Cost Management Systems Division (26). System Program Offices (SPO) for the A-10 (22), F-5 (6), F-15 (4), F-16 (4), and Propulsion Systems (34) were also contacted. In each case, sources of engine cost data were found for the engine level, but only one source of data at the engine section level was located, the F-5 SPO.

The F-5 SPO collects production cost data from the manufacturer for the J-85-21 engine. The data are compiled by General Electric, Lynn, Massachusetts under their own Cost and Schedule Measurement Operating Systems (COSMOS). Copies of COSMOS reports are sent monthly to the F-5 SPO (6). COSMOS compiles engine production cost data by parts, assemblies, sections, and complete engines (14). Discovery of this data led to a further search for COSMOS data on other engines.

COSMOS is presently operational for only two General Electric engines, the J-85-21 and the TF-34-100. Only the J-85-21 data are presently being collected by the SPOs

(6,22). Although the company plans future implementation of the system on other engines (7,28), COSMOS as a data source for this research effort was limited to the J-85-21 and TF-34-100. However, General Electric was willing to provide available production cost data on five other engines to support this research (27,28).

Data collection efforts with two other major engine manufacturers were not as successful. A representative of Pratt and Whitney provided a production cost breakdown for the F-100 engine. However, in the limited time frame of this research and for reasons not explained to the researchers, the Pratt and Whitney representative could not provide data on any other engines (20). Detroit Diesel Allison, according to the Air Force Plant Representative's Office (AFPRO), does not presently collect or segregate engine production cost data by engine section (10).

Finally, the Naval Air Development Center, Warminster, Pennsylvania was contacted as a potential data source. The researchers were informed that the only production cost data presently available and in use by the Navy in engine cost estimating studies were data reflecting total engine production costs. According to the respondent, no source of engine section production cost data existed in the Navy at the time of this research (5).

Data Description

Production cost data for eight engines were collected (see Table 4). Data collected were heterogenous in terms of the following:

1. Engine characteristics.

a. The F-100, F-101, F-404, TF-34-100, and TF-39 are turbofan engines.

b. The J-79-17 and J-85-21 are turbojet engines.

c. The GE-18 (T-700) is a turboshaft engine.

d. The F-100, F-101, F-404, J-79-17, and J-85-21 have an augmentor and nozzle while the others do not.

e. The F-100, F-101, F-404, TF-34-100, TF-39, and GE-18 (T-700) have a low pressure turbine. Others do not.

f. The F-100 is of modular construction. Others are not.

2. Data sources and cost year.

a. The F-100 cost figures were based on actual production costs provided by the manufacturer in 1973 dollars (20).

b. The F-101 engine cost figures were based on manufacturer's cost estimates in 1976 dollars (28).

c. The F-404 engine cost figures were based on manufacturer's cost estimates in 1975 dollars (28).

d. The TF-34-100 engine cost figures were based

Table 4

Engine Section Production Costs (% of Total Production Cost)

Engine	Fan (X1)	Compressor (X2)	Combustor (X3)	High Pressure Turbine (X4)	Low Pressure Turbine (X5)	Bearings Seals Accessories (X6)	Controls & Accessories (X7)	Frames (X8)	Augmentor & Nozzle (X9)
F-100	6.3	18.7	3.1	10.4	5.1	3.1	11.5	7.8	26.0
F-101	7.9	9.8	4.3	11.3	7.5	2.6	14.3	7.3	22.7
F-404	9.9	5.8	3.5	14.4	7.3	2.4	21.0	9.3	8.5
TF-34-100	9.6	10.0	12.6	11.6	13.2	10.2	11.2	4.4	--*
TF-39	19.4	10.9	3.3	11.8	13.2	5.2	3.8	15.9	--*
J-85-21	--*	26.9	3.4	14.8	--*	6.7	24.8	6.1	17.1
J-79-17	--*	29.0	2.8	16.2	--*	5.9	16.5	6.5	13.4
GE-18 (T-700)	--*	3.2	8.1	12.5	9.8	8.3	22.5	9.4	--*

*Engine configuration does not contain this section.

on actual production costs tracked by COSMOS as of 1 July 1976 (7).

e. The TF-39 engine cost figures were based on actual production costs provided by the manufacturer in 1976 dollars (28).

f. The J-79-17 engine cost figures were based on actual production costs provided by the manufacturer in 1973 dollars (28).

g. The J-85-21 engine cost figures were based on actual production costs tracked by COSMOS as of 1 January 1975 (6).

h. The GE-18 (T-700) engine cost figures were based on actual production costs provided by the manufacturer in 1975 dollars (28).

3. Production status.

a. The J-79-17 is no longer in production (28).

b. The F-100, TF-34-100, TF-39, J-85-21, and GE-18 (T-700) were currently in production (7,6,28).

c. The F-101 and F-404 were not yet in production (28).

Table 4 reflects the engine cost data collected for this research. Production costs include direct labor, direct material and overhead apportionment. Some miscellaneous material and assembly, inspection and test costs are not included. At the manufacturers' requests, costs are shown in Table 4 in terms of percent of total production cost to protect the proprietary nature of the actual dollar figures (10,28). Actual dollar costs used for the correlation analysis in this research were retained on file by AFAPL (2).

The lack of homogeniety and variations in the data collected will be treated in the sections on limitations and assumptions that follow.

Population and Sample

The population of interest is comprised of all gas turbine engines (turbojet, turboshaft, and turbofan) produced for use on United States military aircraft. The attributes of interest are production costs for the completed engine and for engine sections.

Data availability and time allocated for this research have limited the sample to one of opportunity. As previously discussed in the data collection section, the available data were not selected by a random sampling procedure. Therefore, the sample cannot be considered representative of the population. Nevertheless, the sample has been judged sufficient to provide an insight into the relationship of total engine production cost and production costs of engine sections (19,24).

Analysis Procedures

Production cost data for engine sections and complete engines conform to the requirements for ratio-level data, which is the highest measurement scale (23:5). Therefore, this ratio-level data satisfies the lower level requirements (interval-level) for correlation analysis (23:280).

Bivariate, or simple pairwise correlation, provides a single number (the coefficient of correlation, r) which summarizes the relationship between two variables (23:276). Using the sub-program PEARSON CORR of the Statistical Package for the Social Sciences (SPSS), the coefficients of correlation were computed to determine the strength of correlation between each engine section production cost and total engine production cost, and between each engine section production cost (23:276).

Partial correlation provides a single measure of association (the coefficient of correlation, r) describing the relationship between two variables while adjusting for the effects of one or more additional variables (23:302). The SPSS sub-program PARTIAL CORR was used for partial correlation analysis. By putting each engine section which demonstrated a high pairwise correlation into a partial correlation analysis with total engine cost, the net effects of selected engine section costs on total engine cost were determined while other section costs were held constant.

Statistical procedures necessary to accomplish the correlation analysis are contained in Appendix B.

Appendix C contains copies of the SPSS programs written to accomplish the simple pairwise correlations of all variables of interest and partial correlations of variables which met the criteria test described in the following section. The correlation analyses were accomplished as follows:

1. Using the data for all eight engines, simple pairwise correlations were calculated for each section cost (X1 through X9) with total engine production cost (TCOST). In addition, simple pairwise correlations were calculated for each section cost (X1 through X9) with each other section (X1 through X9).

2. Partial correlations of section costs with TCOST were calculated for those sections which met the simple pairwise correlation criteria test described in the following section.

Criteria Tests

A criterion test was necessary to determine if the relationships between engine section production costs and total engine production costs identified through this research were "meaningful." The literature review conducted by the researchers failed to identify any previous statistical analyses or studies which attempted to identify such relationships. Further, no objective basis for judging "meaningfulness" was discovered in the literature review. Therefore, the researchers relied upon the value judgement of the research sponsor, AFAPL, to provide a criteria test for "meaningful" relationships.

Any relationship between an engine section production cost and total engine production cost which exhibited a correlation coefficient of 0.7 or greater in simple pairwise correlation or correlation coefficients of not less than 0.4 in partial correlation analysis were judged meaningful by AFAPL (2,24). Previous knowledge of these relationships was limited to other expert opinion, conjecture, and subjective judgement of various personnel familiar with engine design and engine cost estimating (2,24). For example, a commonly held belief is that the cost of the high pressure turbine section correlates highly with total engine cost (24). Therefore, any objective evidence tending to clarify these relationships, such as that demonstrated by correlation analysis using the aforementioned criteria were judged "meaningful" (2,24).

The following criteria were used to answer the research questions:

1. Simple pairwise correlation analysis between engine section production cost and total engine production cost, and between the production costs of engine sections: Computation and display of these correlations answered Research Questions 1 and 2.

2. In answering Research Question 3, the following results of correlation analysis provided an insight into techniques which could be used for predicting production costs and design change costs (24).

a. Simple correlations between each section production and total engine production cost of 0.7 or greater.

b. A section which demonstrates partial correlation coefficients of not less than 0.4 with total engine production cost while controlling for other engine section costs.

Summary List of Limitations

1. Data collected:

a. Because of limited data availability, the data were heterogenous in terms of engine type, section composition and cost year.

b. Production cost data at engine section level could not be located within the Air Force (with the exception of the J-85-21).

c. Time allocated to this research limited the collection of data to that described in the previous data description section.

d. Seven of the eight engines were manufactured by General Electric Corporation. Therefore, conclusions drawn from this analysis may be more applicable to GE engines than those of other manufacturers.

e. Accuracy of data provided by engine manufacturers were limited to the accuracy of their collection of actual and/or estimates of production costs.

f. Modular engine construction (F-100) and conventional engine construction (others) resulted in a dissimilar breakdown of engine modules versus engine sections. To counteract this dissimilarity, F-100 production costs were further broken down under AFAPL supervision to the assembly level. Assembly costs were then aggregated to provide an engine section cost breakdown for the F-100 similar to that of the conventional engines (2). The original allocation of assembly costs to F-100 modules provided by the manufacturer and the resultant re-allocation of assembly costs to engine sections by the researchers with the advice of AFAPL were retained on file by AFAPL (2).

Summary List of Assumptions

1. For the purpose of analysis:

a. Adjustment of production cost data to constant year dollars was not necessary since the proportion of engine section cost to total engine cost remains constant (2).

b. In the population of engines, the defined variables selected for correlation analysis are distributed in a joint bivariate normal distribution as is required for correlation analysis.

2. Breakdown of F-100 module costs to assembly level, and re-aggregation of those costs into engine section costs similar to conventional engine section construction provided F-100 cost data useable in this analysis.

Chapter 3

DATA ANALYSIS AND FINDINGS

This chapter describes the data analysis and subsequent findings in detail. The results of bivariate or simple pairwise correlation and partial correlation analyses of each engine section cost with total engine cost are described. The final section summarizes the findings by addressing the research questions.

BIVARIATE CORRELATION ANALYSIS

Engine Sections with Total Cost

Table 5 depicts the results of simple pairwise correlation of each section production cost with production cost of complete engines. The correlation coefficient (r) is positive for all variables indicating a direct relationship between each section and total cost. The strength of each relationship is provided by the value of r where 1.000 indicates a perfect direct linear relationship, -1.000 indicates a perfect inverse linear relationship, and 0.000 indicates the complete absence of a linear relationship (21:279).

The high pressure turbine (X4) exhibited the highest direct correlation with total engine cost (r = .9954). The augmentor and nozzle (X9) also shows a

Table 5

Simple Pairwise Correlations: Engine Sections With Total Engine Cost

	TCOST (all engines)
X1	.6173
X2	.9058
X3	.8851
X4	.9954
X5	.8237
X6	.8699
X7	.9131
X8	.9054
X9	.9868

very strong direct relationship with TCOST (r = .9868). Other sections which met the criteria test for further analysis (r $\geq$ .7000) are the compressor (X2), combustor (X3), low pressure turbine (X5), bearings, seals and drives (X6), controls and accessories (X7), and frames (X8).

The fan (X1) with an r = .6173 was the only engine section which did not meet the criteria test for further analysis via partial correlation.

Among Engine Sections

Table 6 lists the results of simple pairwise correlation of each section cost with each other section. Positive correlation coefficients indicate direct relationships among all the engine sections.

The lowest correlation between two components was r = .2589 for the fan (X1) and controls and accessories (X7). The highest correlation between two components was r = .9962 for bearings, seals and drives (X6) with the augmentor and nozzle (X9).

The section which exhibited a high correlation with all other sections most consistently was the augmentor and nozzle (X9). Correlation coefficients of X9 with other sections were greater than .9200 except the low pressure turbine, which was .8416.

Table 6

Simple Pairwise Correlations: Among Engine Sections

	X1	X2	X3	X4	X5	X6	X7	X8	X9
X1	1.000	.4745	.3000	.6335	.9365	.6542	.2589	.9277	.9267
X2	.4745	1.000	.7109	.8761	.6391	.8242	.7858	.7903	.9386
X3	.3000	.7109	1.000	.8757	.7495	.8543	.8350	.7280	.9373
X4	.6335	.8761	.8757	1.000	.8410	.8459	.9212	.9111	.9693
X5	.9365	.6391	.7495	.8410	1.000	.8348	.5941	.9181	.8416
X6	.6542	.8242	.8543	.8459	.8348	1.000	.6282	.8782	.9962
X7	.2589	.7858	.8350	.9212	.5941	.6282	1.000	.6917	.9257
X8	.9277	.7903	.7280	.9111	.9181	.8782	.6917	1.000	.9765
X9	.9267	.9386	.9373	.9693	.8416	.9962	.9257	.9765	1.000

The fan (X1) was the only section which exhibited correlation coefficients of less than .500 with any other section. These were the compressor (X3) at .3000 and controls and accessories (X7) at .2589.

In summary, the results of simple pairwise correlation discussed above described the relationships between the production costs of gas turbine engines and engine sections and between the production costs of engine sections. All engine sections with the exception of the fan (X1) exhibited a correlation with TCOST greater than .7000. Partial correlation analysis described in the next section was conducted to determine which of those relationships appeared to be spurious and which appeared to be true.

The results of the simple correlations exhibited no major surprises. It was anticipated that there would be a positive linear relationship between engine section production cost and total engine production cost. The fact that the fan (X1) did not meet the criteria test could be the result of limited data availability or some other reason that the researchers were not qualified to answer (i.e., technological considerations).

PARTIAL CORRELATION ANALYSIS

Further investigation of the relationships between engine section costs and total engine cost was conducted via partial correlation. The purpose was to determine if the engine section costs were in fact correlated as the simple correlation analysis indicated, or if the correlation was due to the fact that a particular section cost correlated with another section which was, in reality, the high correlator with TCOST.

Kendall and Stuart describe the insight into the relationship between two variables provided by partial correlation as follows:

> If we find that holding another variable fixed reduces the correlation between two variables, we infer that their interdependence arises in part through the agency of that other variable; and, if the partial correlation is zero or very small, we infer that their interdependence is entirely attributable to that agency. Conversely, if the partial correlation is larger than the original correlation between the variables we infer that the other variable was obscuring the stronger connection or, as we may say, 'masking' the correlation. But it must be remembered that even in the latter case we still have no warrant to presume a causal connection: . . . the presumption of causality must always be extra-statistical [17:317].

First order partial correlation shows the correlation between two variables while controlling for the effects of a third variable. First order partial correlations were conducted for each engine section which met the criteria test with total cost while controlling for the effects of each other section, one at a time.

Second order partial correlation was used to control for the effects of other engine sections, two at a time, providing further insight into the relationships of section costs and total cost.

Partial correlation analysis was limited to first and second order correlations. Proceeding beyond the second order with such a small sample (eight engines) produced higher order partial correlations which were less meaningful and could have proven misleading (36). First and second order partials were sufficient to clarify the relationships suggested in the previous simple pairwise correlation analysis (36).

Cost data for all eight engines were used to compute the first and second order correlation coefficients for sections common to all engines with total engine production cost: compressor (X2), combustor (X3), high pressure turbine (X4), bearings, seals, and drives (X6), controls and accessories (X7), and frames (X8). The first order coefficients are shown in Table 7. The second order coefficients are shown in Table 8.

Partial correlation analyses of the low pressure turbine (X5) and of the augmentor and nozzle (X9) were conducted separately using only the data for engines which have those sections. Results are discussed separately in sections which follow. Partial correlation analysis of the

Table 7

First Order Partial Correlations: Sections Common to All Engines

TCOST WITH CONTROLLING FOR	X2	X3	X4	X6	X7	X8
X2	--	.8094	.9882	.5139	.7684	.7302
X3	.8452	--	.9805	.4703	.6798	.8183
X4	.7331	.2903	--	.5467	-.1028	-.0374
X6	.6762	.5538	.9867	--	.9554	.5998
X7	.7468	.5468	.9724	.9340	--	.9302
X8	.7316	.7765	.9743	.3682	.9358	--

Table 8

Second Order Partial Correlations: Sections Common to All Engines

TCOST WITH CONTROLLING FOR	X2	X3	X4	X6	X7	X8
X2, X3	--	--	.9828	-.0725	.5605	.7718
X2, X4	--	.7084	--	.4810	-.0295	-.0124
X2, X6	--	.7307	.9876	--	.9305	.6074
X2, X7	--	.6500	.9708	.8711	--	.9337
X2, X8	--	.8374	.9744	.0708	.9421	--
X3, X4	.8651	--	--	.4875	-.1548	.0721
X3, X6	.7969	--	.9809	--	.9728	.7829
X3, X7	.7973	--	.9643	.9604	--	.9332
X3, X8	.8064	--	.9400	-.2958	.8887	--
X4, X6	.7021	.0657	--	--	.5135	-.4170
X4, X7	.7300	.3109	--	.6915	--	-.3390
X4, X8	.7327	.2962	--	.6480	-.3507	--
X6, X7	.4052	-.7570	.8817	--	--	.8793
X6, X8	.6819	.7621	.9829	--	.9844	--
X7, X8	.7611	.5730	.8016	.8861	--	--

fan (X1) was not conducted since the simple correlation of the fan with TCOST did not meet the criteria test ($r \geq .7000$).

Results of partial correlation analyses of each section with TCOST follow. Histograms are used to display the zero order (simple pairwise), first order, and second order partial correlation coefficients. Coefficients displayed were rounded to two significant digits. Spurious correlation between the engine section and TCOST is indicated when the value of r for the zero order correlation decreases as the effects of other sections are controlled in the first and second order partial correlations.

Negative correlation coefficients occurred in a number of first and second order partial correlations. Such coefficients were a result of the method used in calculating partial correlations and are not necessarily indicative of an inverse relationship. However, the occurrence of negative correlation coefficients does serve to further indicate the spurious nature of the relationship between two variables (23:303).

Compressor (X2)

The zero order correlation of .9058 with TCOST holds up reasonably well when the effects of the other engine sections are controlled, as shown in Figure 5. The minimum

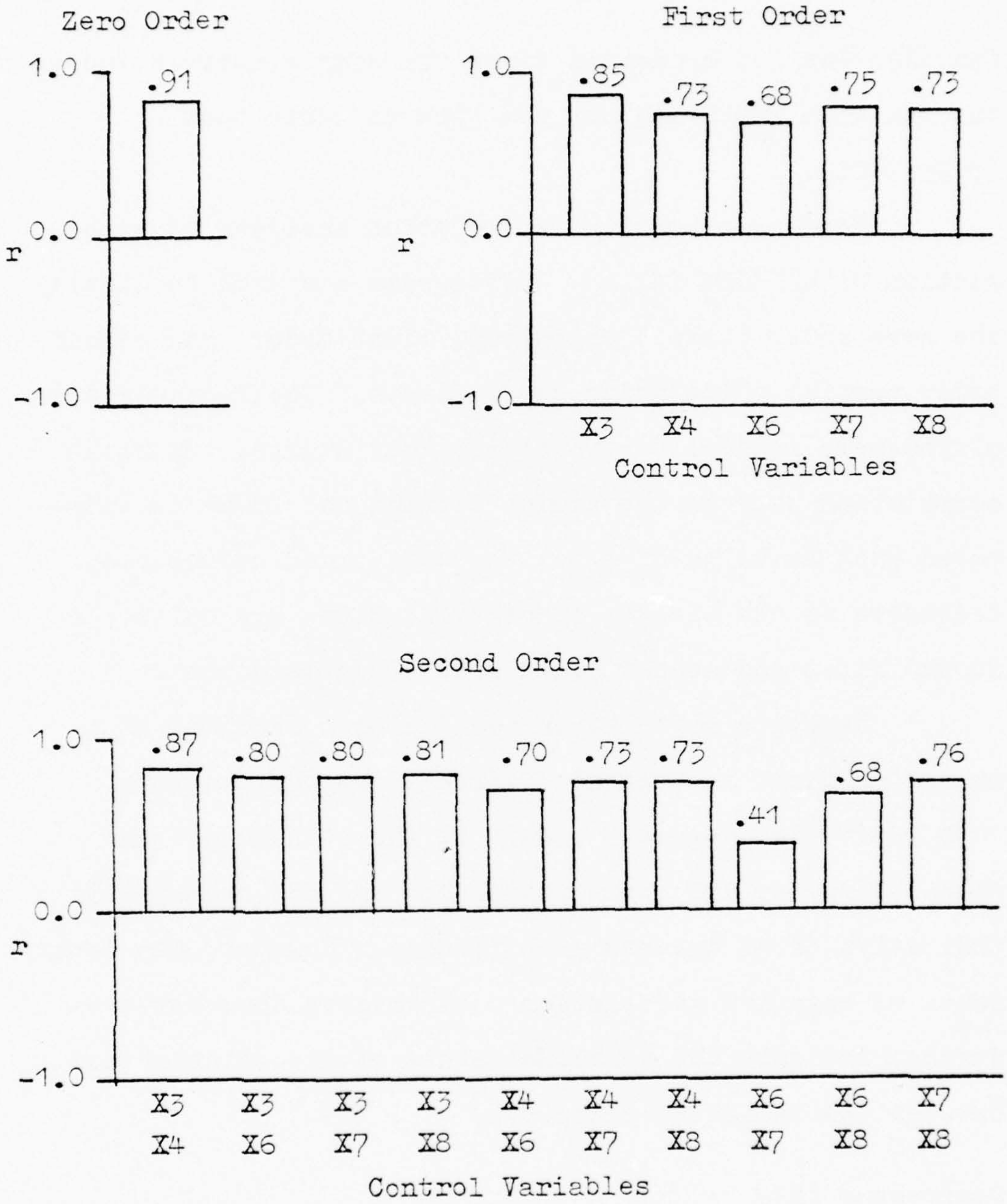


Figure 5

Partial Correlation Coefficients: TCOST with X2

first order correlation coefficient is .6762 when the effect of bearings, seals and drives (X6) is controlled.

Combustor (X3)

The simple pairwise correlation of .8851 with TCOST does not hold up under partial correlation, particularly when the effect of the high pressure turbine (X4) is controlled. Figure 6 shows first and second order partial correlation coefficients which indicate much of the correlation of X3 with TCOST is spurious.

High Pressure Turbine (X4)

The simple pairwise correlation of .9954 holds up extremely well under partial correlation analysis. Results shown in Figure 7 indicate that the high pairwise correlation is not due to the effects of other sections. Rather, the high correlation of X4 with TCOST appears to be a true direct correlation.

Bearings, Seals, and Drives (X6)

The simple pairwise correlation of .8699 appears to be largely spurious. Even though, X7 appears to "mask"[1] some of the correlation between X6 and TCOST, when the effects of the other variables are controlled, the true

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[1] For definition of "mask" see page 37.

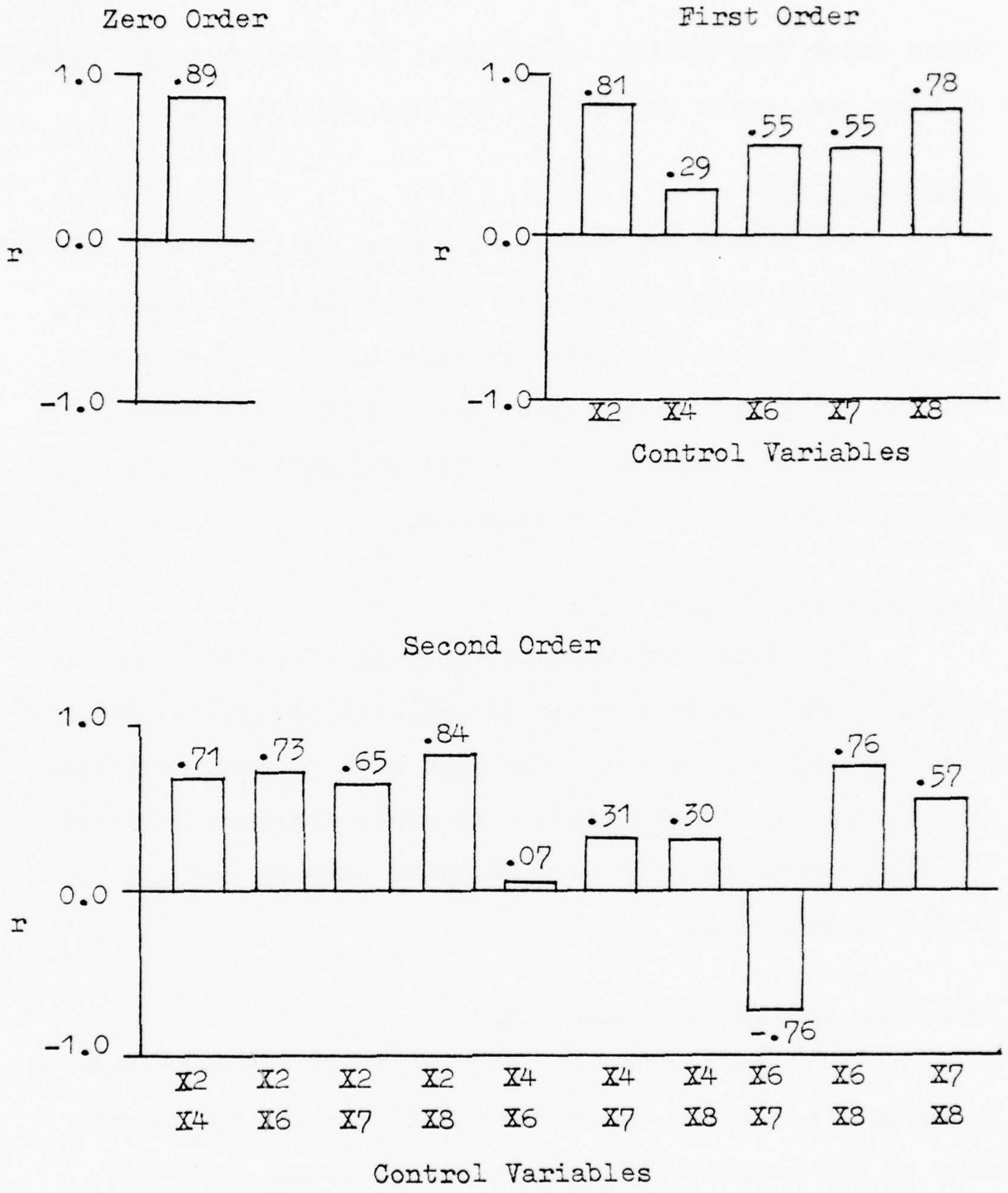

Figure 6

Partial Correlation Coefficients: TCOST with X3

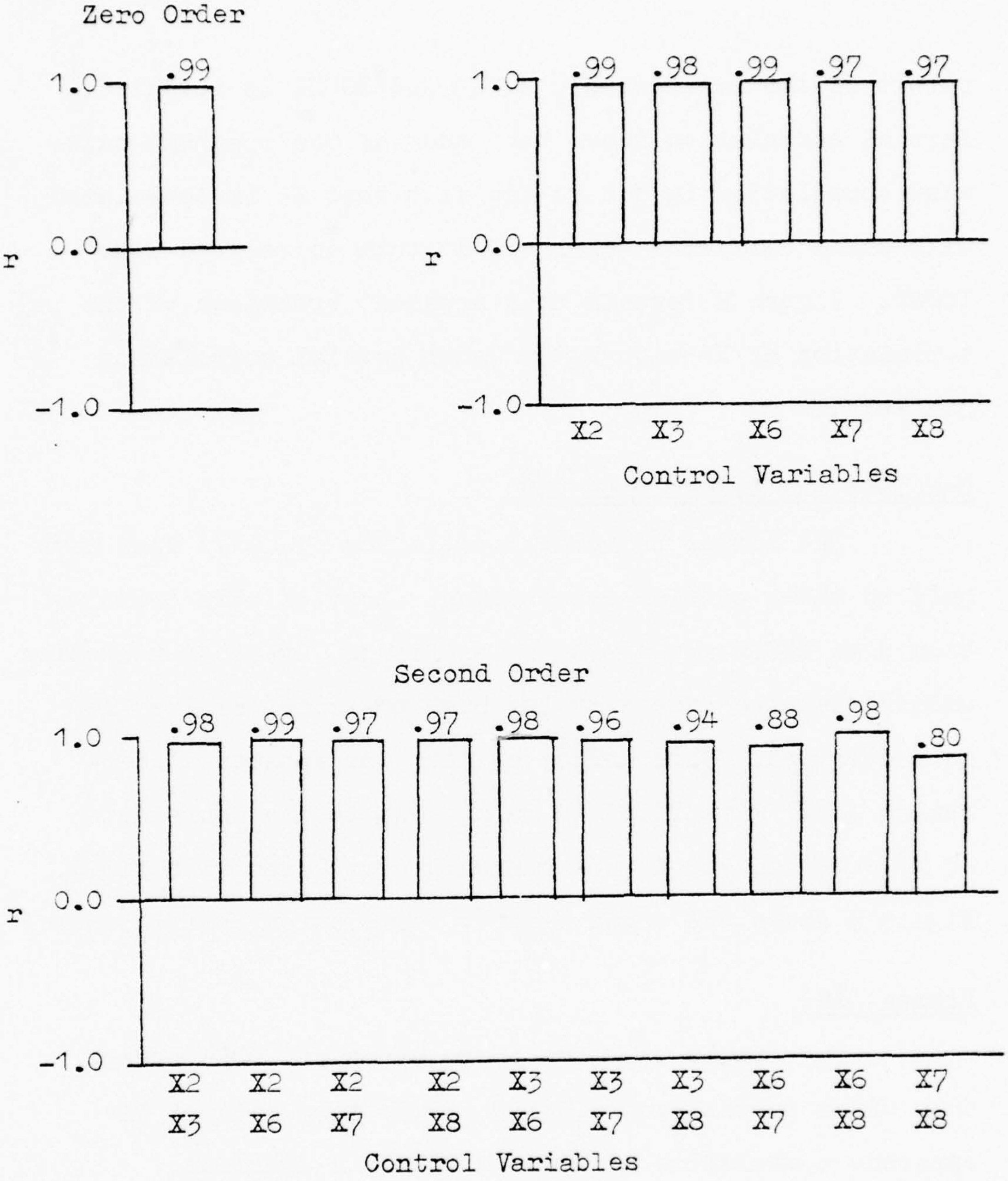

Figure 7

Partial Correlation Coefficients: TCOST with X4

nature of the relationship of X6 and TCOST is revealed. Partial correlation shows that much of the apparent pairwise correlation is due to the fact that X6 is correlated with other variables which are in turn correlated with TCOST. Figure 8 reveals this apparent breakdown of the correlation of X6 with TCOST under partial correlation analysis.

Controls and Accessories (X7)

The simple pairwise correlation of .9131 does not hold up under partial correlation. Most of this correlation with TCOST appears to be spurious. Greatest reduction occurs when the effect of the high pressure turbine (X4) is controlled. This indicates that the apparent correlation of X7 with TCOST is mainly due to the correlation of X7 with X4, and X4 being highly correlated with TCOST. Figure 9 shows the comparison of correlation coefficients.

Frames (X8)

The simple pairwise correlation of .9054 breaks down under partial correlation, indicating much of the apparent correlation of X8 with TCOST is spurious. Greatest reduction in value of the correlation coefficient occurs when the effect of the high pressure turbine (X4) is controlled. Figure 10 illustrates the partial correlation coefficients.

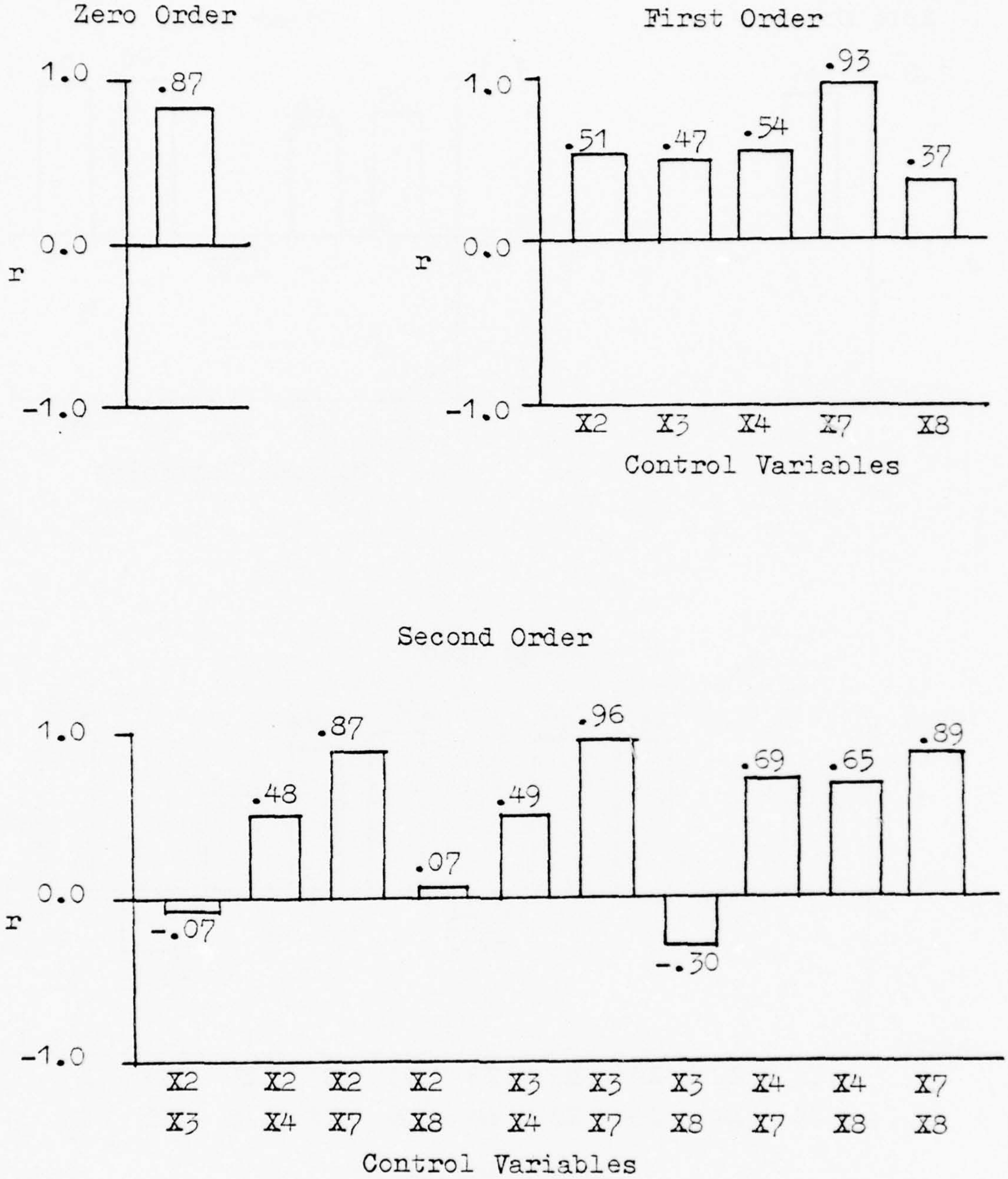

Figure 8

Partial Correlation Coefficients: TCOST with X6

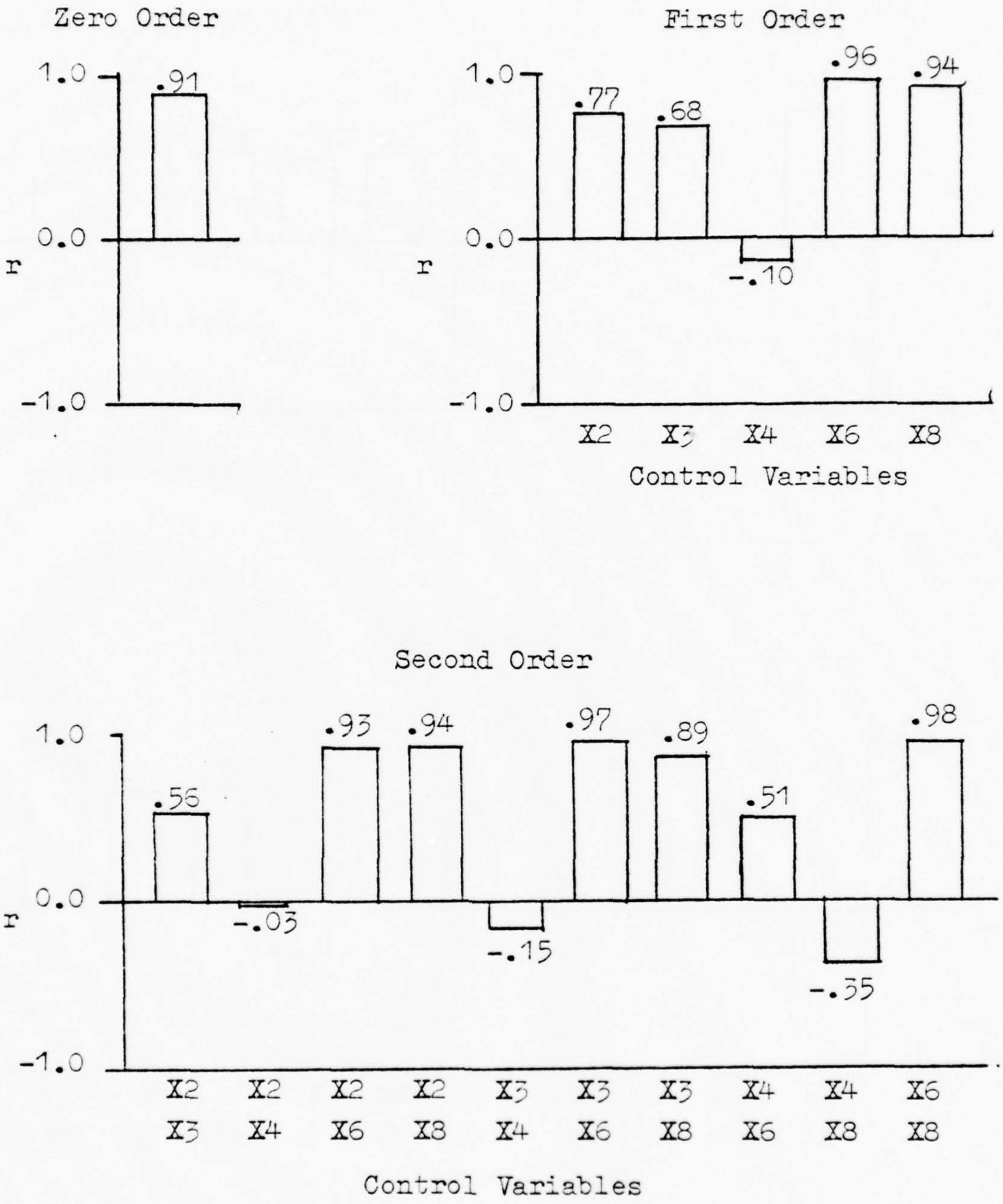

Figure 9

Partial Correlation Coefficients: TCOST with X7

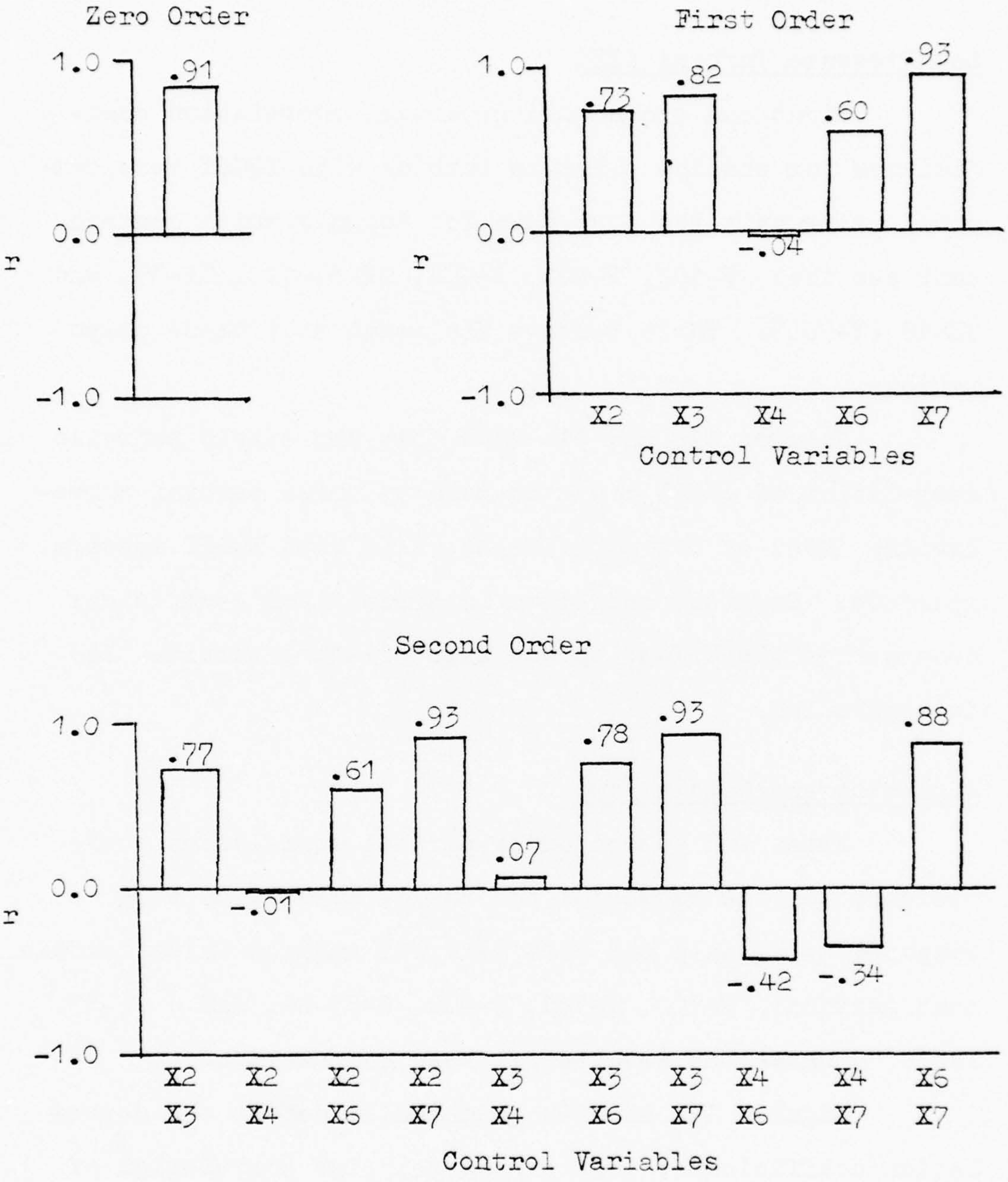

Figure 10

Partial Correlation Coefficients: TCOST with X8

Low Pressure Turbine (X5)

First and second order partial correlation coefficients for the low pressure turbine with TCOST were computed using only the cost data for engines which contain that section: F-100, F-101, F-404, TF-34-100, TF-39, and GE-18 (T-700). Table 9 shows the results of these computations.

Figures 11a and 11b show that the simple pairwise correlation of .8699 does not hold up under partial correlation. Most of the correlation of X5 with TCOST appears spurious. Greatest reduction in correlation coefficient occurs when the effect of the high pressure turbine (X4) is controlled.

Augmentor and Nozzle (X9)

First and second order partial correlation coefficients for the augmentor and nozzle with TCOST were computed using only the cost data for engines which contain that section: F-100, F-101, F-404, J-85-21, and J-79-17. Table 10 shows the results of these computations.

Figures 12a and 12b graphically depict the correlation coefficients. The simple pairwise correlation of .9868 appears to hold up well in first order partial correlation. However, when the effects of other sections are controlled two at a time in second order partial correlation,

Table 9

First and Second Order Partial Correlations:

Low Pressure Turbine

First Order

Controlling for: \ TCOST With	X5
X2	0.7897
X3	0.5342
X4	-0.2190
X6	0.4292
X7	0.8213
X8	0.1021

Second Order

Controlling for: \ TCOST With	X5
X2, X3	0.6838
X2, X4	0.2805
X2, X6	0.9056
X2, X7	0.9950
X2, X8	0.6760
X3, X4	-0.2767
X3, X6	0.3495
X3, X7	0.7627
X3, X8	-0.8813
X4, X6	-0.7143
X4, X7	-0.4894
X4, X8	-0.2435
X6, X7	0.4815
X6, X8	-0.0194
X7, X8	.0909

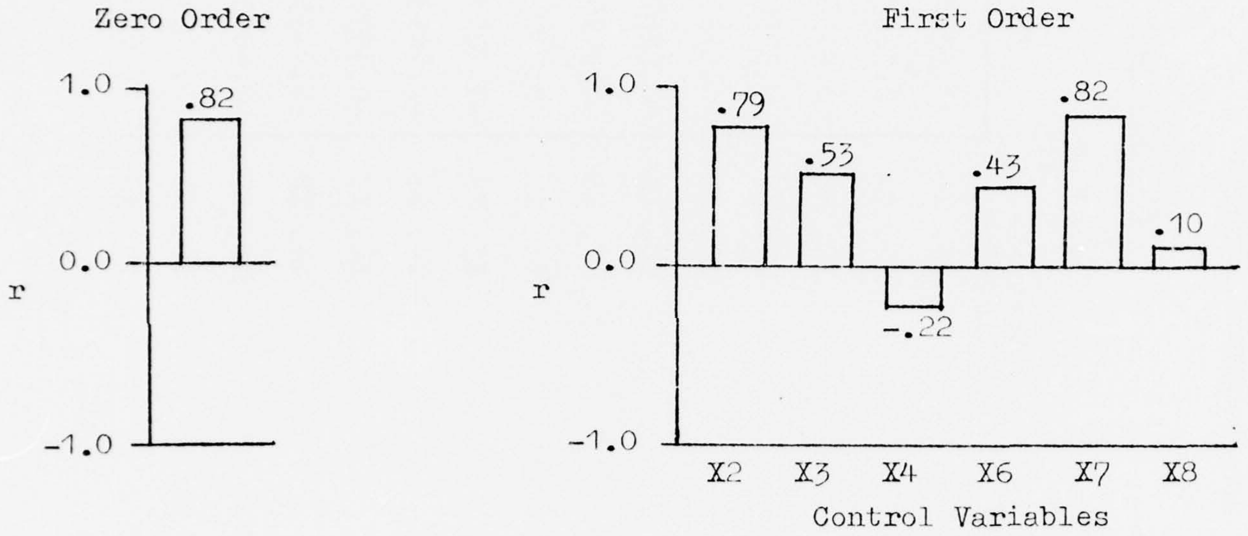

Figure 11a

Zero and First Order Partial Correlation

Coefficients: TCOST with X5

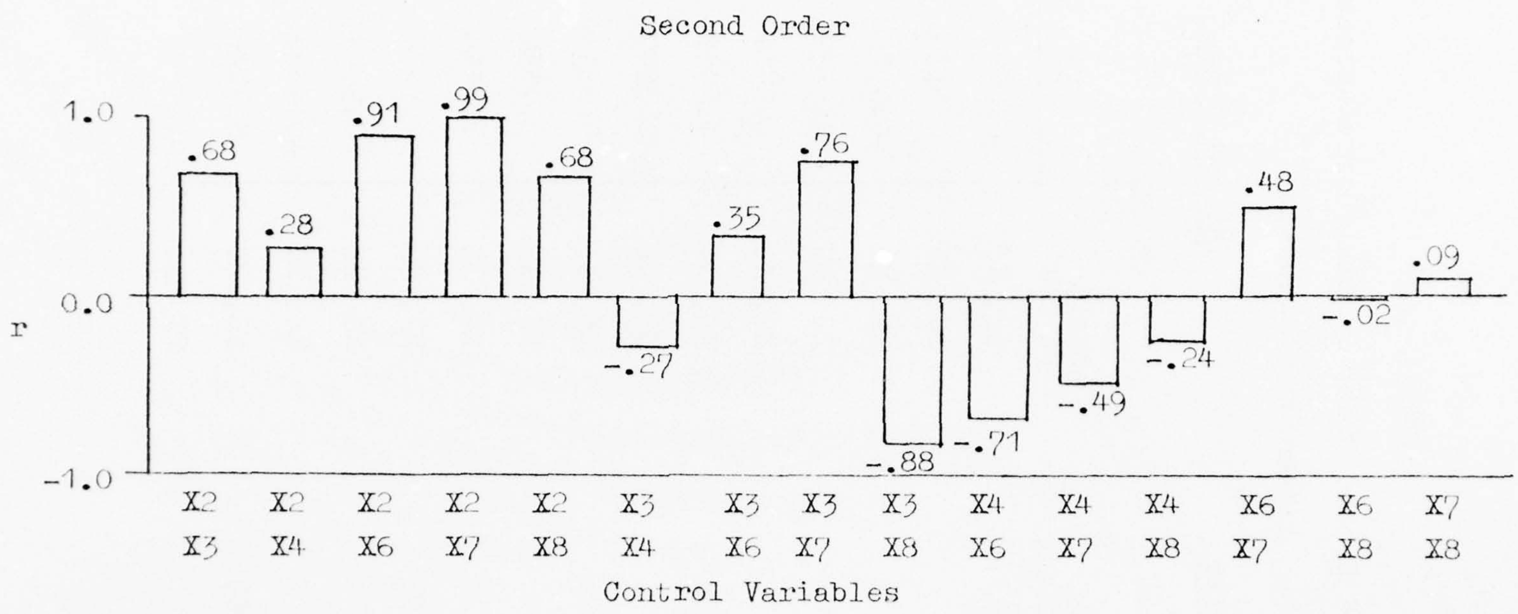

Figure 11b

Second Order Partial Correlation

Coefficients: TCOST with X5

Table 10

First and Second Order Partial Correlations: Augmentor and Nozzle

First Order

Controlling for	TCOST With X9
X2	.9655
X3	.9168
X4	.9898
X6	.7475
X7	.9855
X8	.7269

Second Order

Controlling for	TCOST With X9
X2, X3	-0.7023
X2, X4	0.9534
X2, X6	-0.4554
X2, X7	0.8832
X2, X8	0.9764
X3, X4	0.9912
X3, X6	-0.5647
X3, X7	0.9914
X3, X8	0.9854
X4, X6	0.8636
X4, X7	0.9774
X4, X8	0.9944
X6, X7	-0.4687
X6, X8	0.9046
X7, X8	0.9749

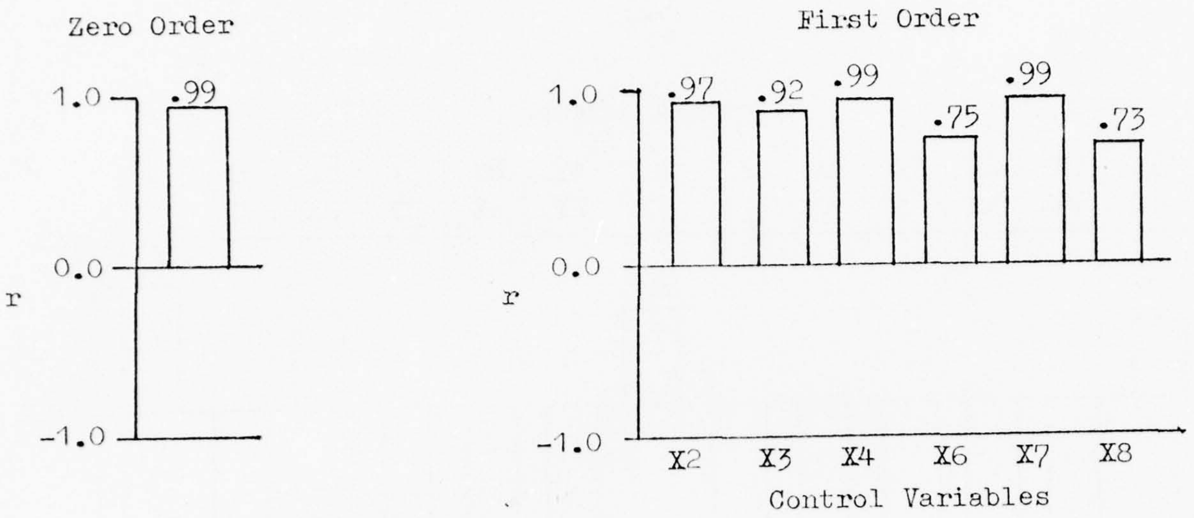

Figure 12a

Zero and First Order Partial Correlation

Coefficients: TCOST with X9

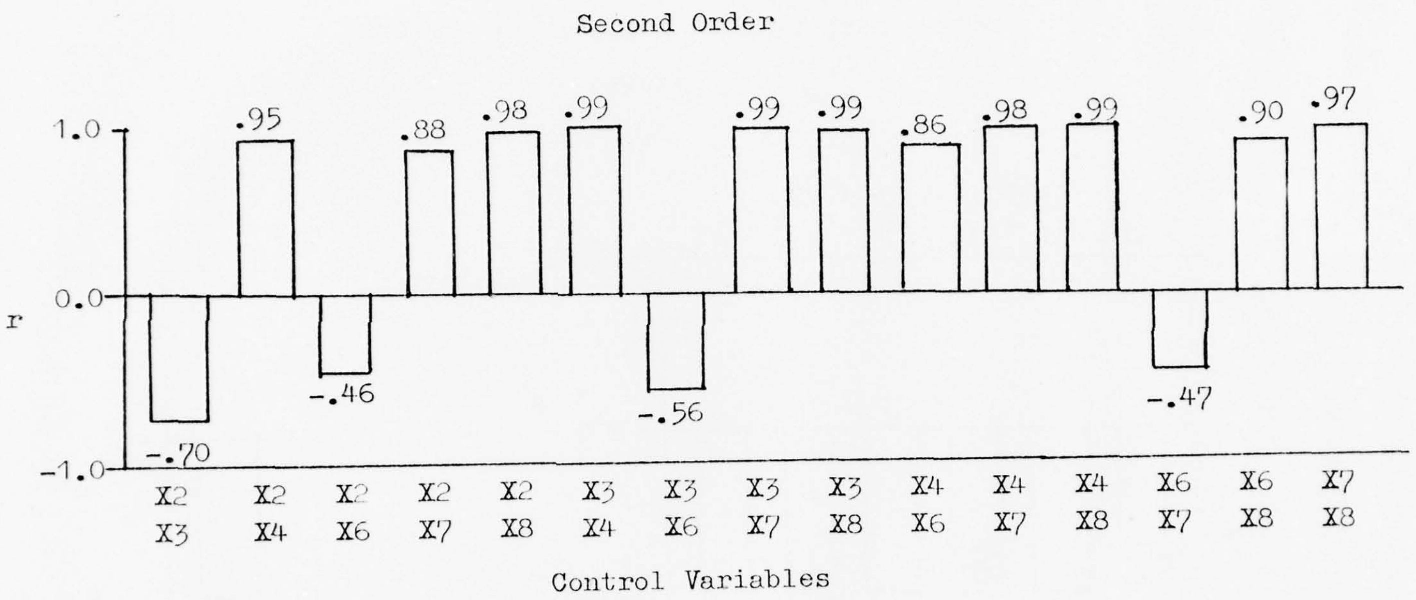

Figure 12b

Second Order Partial Correlation

Coefficients: TCOST with X9

much of the simple correlation appears spurious. In particular, X3 and X6, appear to have a major effect.

Due to the limited number of engines (five) used for this analysis, the results should be labeled inconclusive.

In summary, partial correlation analysis has provided further insight into and clarification of the relationships between engine section production cost and total engine production costs. First and second order partial correlation indicates that the initial high direct correlation is largely spurious for sections other than the compressor (X3) and high pressure turbine (X4). Further, much of the correlation of other sections with TCOST is apparently to be due to the fact that those sections correlate with the high pressure turbine; and the high pressure turbine is, in fact, correlated with TCOST. Of the variables analyzed (X2 through X9), the high pressure turbine demonstrated the highest direct, true correlation with total engine production cost.

Answers to Research Questions

Research Question 1. What is the relationship between engine section production costs and total engine production costs?

All engine sections demonstrated a direct correlation with total engine cost. The high pressure turbine exhibited the highest direct correlation and partial correlation showed this to be, for the most part, a true correlation. The fan exhibited the lowest direct correlation with total engine cost and was the only engine section which did not meet the criteria test for further analysis via partial correlation. The compressor exhibited a high direct correlation with total engine production cost which held up fairly well under partial correlation, although not as well as the high pressure turbine. The direct correlations with total engine section production costs exhibited by the remaining engine sections were not maintained once the effects of other sections were controlled. This indicated that much of the simple pairwise correlation was spurious.

Research Question 2. What are the relationships between the production costs of engine sections?

All simple pairwise correlations between engine section costs were positive indicating direct relationships. The augmentor and nozzle exhibited a high direct correlation with the other sections most consistently. The fan exhibited the lowest direct correlation with the other sections.

Research Question 3. Do these relationships provide insight into techniques which could be used for predicting production costs and design change costs of gas turbine engines?

As a result of the research, this question can be answered affirmatively. Analysis results indicate that the techniques of regression analysis and the industrial engineering approach could be used.

The high correlation of high pressure turbine and compressor production costs with total engine production costs provides evidence of the feasibility of regression analysis. These two sections would be the prime candidates for independent variables in simple linear regressions (SLR) or multiple linear regressions (MLR) against the dependent variable, total engine cost.

The high direct correlation of the high pressure turbine with total engine production cost provides implications for the industrial engineering approach to engine cost estimating. Very little of the direct correlation was shown to be spurious. If an accurate estimated cost of the high pressure turbine could be "built up" using the industiral engineering approach, the resultant estimated cost could then be used in simple linear regression to provide an estimate of total engine production cost. Similar efforts with the compressor section might also prove fruitful.

Chapter 4

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Overview

This study has investigated the feasibility of nonparametric cost estimating by using correlation analysis to determine the relationship of engine section production cost to total engine production cost. First in this chapter remarks are made regarding previous research and data availability. Next, conclusions as to the methodology used and the findings produced are discussed, followed by the implications of these findings for cost estimating. Finally, recommendations as to future data collection and further research are proposed.

The lack of production cost data at the engine section level was recognized by the researchers and the sponsors of this research effort as a potential deficiency of this study. Due to this sample size inadequacy inferences to the population of gas turbine engines could not be made. However, the researchers believe that because of data differences of turbine engine type, section composition, cost year and technology, any strong correlations that occur are indicative of the population of gas turbine engines.

In the opinion of the researchers, the results of this study lend credence to the expert opinion that the high pressure turbine is the major determinant of total engine cost.

Previous Research

Three previous research studies were sponsored by AFAPL as part of an on-going effort to establish a creditable engine acquisition costing model. This research constitutes the fourth such effort.

Duetsch and Barry of Georgia Institute of Technology investigated industrial engineering and parametric approaches to engine cost estimating. They voiced preference for the industrial engineering approach but felt that both approaches were overly dependent on a cost model. Their recommendations were that AFAPL construct a manufacturing line simulation to provide a cost model which would reflect the manufacturing environment (9). However, such a simulation would require skill and data resources not presently available to AFAPL (24).

Drake, Reda, and Allen of Purdue University conducted a survey of production cost estimating techniques used in industry and reached two major conclusions. First, the researchers felt that the industrial engineering approach was feasible for AFAPL if personnel with the necessary skills were acquired and access could be gained to engine manufacturing processes and data. The second conclusion was that regression analysis could be used at lower levels (section, assemblies, parts) to predict engine production cost, but that difficulties would be encountered due to differences in engine configuration, design approaches and technology. They asserted these difficulties could be overcome by proceeding to the assembly and/or part level for regression analysis (11). In a follow-on study Drake, Reda, and Allen used the industrial engineering approach to "build up" the cost of a single turbine disk of the J-69-T-25 engine. The study required seven months to complete (12). Such detailed analysis and data acquisition in terms of estimating production costs of a complete engine are clearly beyond the present capability of AFAPL (24).

Mullineaux and Yanke of the Air Force Institute of Technology conducted a study which resulted in improvements in regression models developed by the RAND Corporation for use in the parametric approach to engine cost estimating (21).

By adding statistical verification and raw material factors to the RAND models the researchers provided improved parametric models now in use by AFAPL (24).

As stated in Chapter 1, the objective of this research was to determine the relationship of section production costs to total production cost of gas turbine engines. These relationships provide AFAPL a direction for future research to develop an engine cost estimating methodology (24).

Data Availability

The research required production cost data for complete engines as well as for engine sections. The researchers were successful in locating such data on only eight gas turbine engines.

Attempts to locate data on engine section production costs within the Air Force were, for the most part, unsuccessful. Within the Comptroller, Aeronautical Systems Division, Air Force Systems Command, such data were not available from the Comptroller Cost Library, Life Cycle Cost Library or Cost Management Systems Division. Of the System Program Offices (SPO) contacted, only the F-5 SPO collected and utilized production cost data below the complete engine level that was consistent with the breakdown used in this study. The F-15 and F-16 SPOs collected and utilized production cost data by module (F-100 engine) but did not have any further breakdown of the cost data. Although the General Electric COSMOS system produces detailed cost control data on the TF-34-100 to conform with Air Force Cost/Schedule Control System Criteria the A-10 SPO apparently neither asks for nor utilizes this data. The researchers had to go to the manufacturer for a copy of this COSMOS report.

Engine production cost data broken down to section level were not available from the Navy. Although personnel at the Naval Air Research and Development Center acknowledged plans to collect such data in conjunction with cost estimating research, such efforts to begin data collection were more than a year away.

Efforts to collect engine production cost data from major engine manufacturers met with varied degrees of success. General Electric Corporation provided data on seven engines. A Pratt and Whitney Aircraft Company representative provided data on the F-100 engine and indicated similar data on other engines were not available (20). Finally, a representative of the Air Force Plant Representative Office at Detroit Diesel Allison indicated that production cost data on Allison engines were not collected or aggregated by engine sections (10).

Despite the problems encountered in acquiring data for this research, the researchers are of the opinion that engine production costs can be collected by the manufacturers and aggregated to part, assembly and section costs. If engine production cost data in this format are deemed of value for cost estimation, it remains for the Air Force to ask for, or contract for, such data.

Methodology and Findings

The use of partial correlation analysis provided an effective means of understanding the relationships between two independent variables. It must be remembered that the coefficient of correlation is merely an indication of the linear relationship between two independent variables. It should not be concluded that the numbers represent cause and effect relationships. The presumption of causality " . . . must always be extra-statistical [17:317]."

When computing partial correlation coefficients to the second order the relationships between two variables are indicated by the consistency of the coefficient. Good correlators have little variance in correlation coefficients throughout the analysis, whereas, correlators whose high, positive, zero-order coefficients are spurious in nature have higher order coefficients that vary about zero or are negative.

It is felt by experts that the high pressure turbine is the main cost determinant of gas turbine engines, and that if the cost of this section can be determined then the cost of the engine can be predicted (24). This research tends to show from its limited sample that the high pressure turbine is the best consistent correlator with total production cost and, therefore, tends to substantiate the "gut feeling" of the experts.

Partial correlation analysis has also shown the compressor to be the most consistent correlator with total production cost despite its zero-order correlation being average relative to the other components. This section might also be considered by itself or in conjunction with the high pressure turbine in producing a model to predict engine production costs.

The remaining engine sections did not hold up under partial correlation analysis as indicated by their near zero and/or negative correlation coefficients. Most of their correlation with total production cost is attributable to one or more other section's correlation with total cost.

In summary, partial correlation analysis has appeared to be a viable method in this study in determining the relationship of section production costs to total engine production cost of gas turbine engines. In the analysis, the high pressure turbine appeared to be the best correlator with total production cost thus supporting the opinion that this section is the main cost determinent of total engine production costs.

Implications for Cost Estimating

The findings of this research provide insight into techniques that could be used for predicting production costs of gas turbine engines. Correlation analysis is a reasonable, legitimate predecessor to regression analysis (19). This research indicates that the production cost of the high pressure turbine and the compressor could be entered separately into individual simple linear regressions (SLR) or together into a multiple linear regression (MLR) in an effort to predict total engine production cost.

A logical step in determining the cost of the section to predict total production cost would be to use the industrial engineering approach. If the cost of the high pressure turbine or the compressor could be "built up" then the resultant cost could be used in a SLR to predict total production cost.

Recommendations

Data collection. Data collection problems encountered in this research indicate that sufficient engine cost data for non-parametric approaches to engine cost estimating are not presently collected by the Air Force. Also, methods of reporting and collecting production cost data on completed engines are dissimilarly reported by each manufacturer and dissimilarly collected by each SPO.

It is recognized that the Air Force Cost/Schedule Control System Criteria do not place specific requirements on collection or formatting of production cost data. Nevertheless, further progress in non-parametric cost estimating techniques, particularly the industrial engineering approach, requires production cost data for engines broken down into section, assembly and part levels in a consistent fashion.

Further study. The researchers believe the findings of this study have provided insight into the relationships which exist among production costs in the population of aircraft gas turbine engines. Based upon these findings, the following areas are recommended for further study relative to cost estimating for gas turbine engines.

1. Since the high pressure turbine tended to be the most consistent, direct correlator with total engine cost, efforts should be made to develop a methodology to determine the cost of this engine section. A study to determine the costs of high pressure turbine assemblies and parts in an effort to "build up" high pressure turbine costs using the industrial engineering approach is recommended.

2. Various simple and multiple linear regression models should be built using engine section costs as regressors against total engine cost. Such a study could use the

data collected for this research for building the regression models, but would require collecting data on several other engines for use in testing the prediction accuracy of the models. Such models could also be exercised to predict the effects of design changes within engine sections on total engine cost.

3. A feasibility study should be undertaken to determine the costs versus benefits of requiring contractors to report engine production costs by sections, assemblies, and parts in the manner used in the General Electric COSMOS system. The costs/benefits should be weighed against the feasibility of changing the Cost/Schedule Control System Criteria to require cost reporting in such a format.

4. A comparative analysis of engine parts costs for replacement parts purchased by Air Force Logistics Command (AFLC) versus costs of complete engines should be undertaken. Such a study would provide insight into the feasibility of using AFLC parts cost data in the industrial engineering approach to engine cost estimating.

5. The researchers assumed in this study that normalizing engine cost data to a base year (using index numbers) was not necessary since, within each engine, the proportion of section costs to total cost would remain the same. The researchers believe a study to determine the

validity of this assumption would provide insight into the relationship of costs associated with technological advances in materials and manufacturing methods.

APPENDIX A

DEFINITION OF TERMS

APPENDIX A

1. Assembly: "A number of parts joined together to perform a specific function and capable of disassembly [31:Atch 3]."

2. Engine: "The complete engine [31:Atch 3]."

3. Engine Levels: Breakdown of the complete engine into sections, assemblies, and parts (31:Atch 3).

4. Engine Production Costs: Shop costs required to assemble and test the completed engine (14). Shop costs of engine sections, assemblies, and parts enter this level as direct material costs.

5. Part: "One piece, or two or more joined together which are not normally disassembled without destruction of desired use [31:Atch 3]." For example:

   a. Combustor Basket
   b. Compressor Blade
   c. Exhaust Diffuser

6. Production Cost: Manufacturing shop cost of a part, assembly, section, or complete engine (28).

7. Section: "The immediate functional breakdown below the engine level [31:Atch 3]." For example:

   a. Fan
   b. Compressor
   c. Combustor
   d. Turbine

8. Section Production Costs: Total shop costs required to assemble and test a complete engine section (14). Shop costs of engine assemblies and parts enter this level as direct material costs.

9. Shop Cost: Comprised of the following cost elements: Direct labor and material, and indirect labor and material. These costs typically comprise 75 percent of total engine selling price (18:14).

APPENDIX B

VALIDATION OF ANALYSIS PROCEDURES

Correlation Analysis

Simple correlation analysis provides a numerical representation of the bivariate distribution of two random variables. A correlation coefficient summarizes the strength of the relationship exhibited between the two variables by expressing the change in one variable in relation to the other (23:280).

Multiple correlation is the simple correlation of a single variable and the corresponding linear relationship of other variables. Once the relationship among the variables is known, the net effect of one variable on another in isolation can be determined (35:310).

Covariance

Covariance is a measure of the degree to which two variables are linearly related. Let X and Y be two random variables. Two new variables can be defined as the deviations of X and Y from the means of their respective populations:

$$\begin{gathered} X - u_X \\ Y - u_Y \end{gathered} \tag{1}$$

The covariance of X and Y, σ_{XY}, is defined as the expected value of the product of these two variables:

$$\sigma_{XY} = E[(X - u_X)(Y - u_Y)] \tag{2}$$

Positive covariance indicates the tendency of X and Y to move in the same direction and negative indicates the tendency to move in opposite directions. Since σ_{XY} measures the extent to which the variables move together, if X and Y are independent then $\sigma_{XY} = 0$ (35:91).

Population Correlation Coefficient

While the covariance of X and Y gives an indication of the orientation of the population distribution (X, Y), the population correlation coefficient, ρ_{XY}, gives an indication of the compactness of the distribution. ρ_{XY} is, therefore, a measure of joint central tendency with respect to a line (19).

$$\rho_{XY} = \frac{\sigma_{XY}}{\sigma_X \; \sigma_Y} \tag{3}$$

However, ρ_{XY} is generally unknown and the sample correlation coefficient, r_{XY}, is used as an estimate (35:286).

The Sample Correlation Coefficient

Where X_i and Y_i are random variables, sample observations from the population (X, Y), the sample correlation coefficient, r, is calculated:

$$r = \frac{\Sigma(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\Sigma(X_i - \overline{X})^2 \;\; \Sigma(Y_i - \overline{Y})^2}} \tag{4}$$

r is an unbiased estimator of the population parameter, (35:289-91).

Simple Pairwise Correlation

Simple pairwise correlation involves computation of r for each pair of random variables among a group of variables from a sample. The value of r obtained describes the degree of association between those two variables (8:544). r provides an indication of the strength and direction of a linear relationship between the two variables. r can take on values from -1.0 to 1.0, with -1.0 indicating a perfect inverse linear relationship, 1.0 indicating a perfect direct relationship, and 0 indicating the absence of a linear relationship (23:279).

Partial Correlation

Partial correlation is a simple correlation between two residuals from which the effects of one or more other variables have been removed or controlled (23:333). For example, the correlation of the variables 1 and 2 controlling for a third variable, 3, would be written $r_{12.3}$.

The first order correlation coefficient controlling for one variable, is determined using the zero-order, simple pairwise, coefficients as given by the following formula (23:302):

$$r_{ij \cdot k} = \frac{r_{ij} - r_{ik}\, r_{jk}}{\sqrt{1 - r_{ik}^2}\sqrt{1 - r_{jk}^2}} \qquad (5)$$

Each succeeding ordered correlation coefficient, controlling for n variables, is determined using the (n - 1) ordered partial coefficients (23:303). For example, the second order partial correlation coefficient of the relationship between the two variables i and j controlling for the effects of the variables k and m would be calculated using the formula:

$$r_{ij \cdot km} = \frac{r_{ij \cdot m} - r_{ik \cdot m}\, r_{jk \cdot m}}{\sqrt{1 - r_{ik \cdot m}^2}\sqrt{1 - r_{jk \cdot m}^2}} \qquad (6)$$

APPENDIX C

COMPUTER PROGRAMS USED IN COMPUTING PEARSON CORRELATIONS AND PARTIAL CORRELATIONS

APPENDIX C

SPSS Program for Computing Pearson (Simple Pairwise) Correlations, X1 to X9 with TCOST

```
010##S,R(SL) :,8,16;;,16
020$:IDENT:WP1191,AFIT/SLG  GREENE & STARK
030$:SELECT:SPSS/SPSS
040RUN NAME;ENGINE COST ANALYSIS
050VARIABLE LIST;TCOST,X1 TO X9
060VAR LABELS;TCOST,ENGINE PRODUCTION COST/
070;X1,FAN/
080;X2,COMPRESSOR/
090;X3,COMBUSTOR/
100;X4,HIGH PRESSURE TURBINE/
110;X5,LOW PRESSURE TURBINE/
120;X6,BEARINGS SEALS AND DRIVES/
130;X7,CONTROLS AND ACCESSORIES/
140;X8,FRAMES/
150;X9,AUGMENTOR AND NOZZLE/
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;DISK
180N OF CASES;8
190MISSING VALUES;X1,X5,X9(0)
200READ INPUT DATA
210PEARSON CORR;TCOST,X1 TO X9 WITH TCOST,X1 TO X9
220FINISH
230$:DATA:08
240$:SELECTA:77A68/ENGINE1,R
250$:ENDJOB
```

APPENDIX C

SPSS Program for Computing First and Second Order Partial Correlations of X2, X3, X4, X6, X7, and X8 with TCOST

```
010##S,R(SL) :,8,16;;,16
020$:IDENT:WP1191,AFIT/SLG  GREENE & STARK
030$:SELECT:SPSS/SPSS
040RUN NAME;ENGINE COST ANALYSIS
050VARIABLE LIST;TCOST,X1 TO X9
060VAR LABELS;TCOST,ENGINE PRODUCTION COST/
070;X1,FAN/
080;X2,COMPRESSOR/
090;X3,COMBUSTOR/
100;X4,HIGH PRESSURE TURBINE/
110;X5,LOW PRESSURE TURBINE/
120;X6,BEARINGS SEALS AND DRIVES/
130;X7,CONTROLS AND ACCESSORIES/
140;X8,FRAMES/
150;X9,AUGMENTOR AND NOZZLE/
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;DISK
180N OF CASES;8
190MISSING VALUES;X1,X5,X9(0)
200READ INPUT DATA
210PARTIAL CORR;TCOST WITH X2,X3,X4,X6,X7,X8 BY
220;X2,X3,X4,X6,X7,X8(1,2)
230OPTIONS;2,7
240STATISTICS;1
250FINISH
260$:DATA:08
270$:SELECTA:77A68/ENGINE1,R
280$:ENDJOB
```

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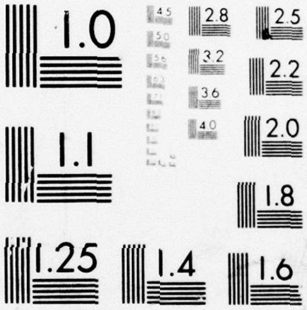

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APPPENDIX C

SPSS Program for Computing First and Second Order Partial Correlations of X5 with TCOST

```
010##S,R(SL) :,8,16;;,16
020$:IDENT:WP1191,AFIT/SLG  GREENE & STARK
030$:SELECT:SPSS/SPSS
040RUN NAME;ENGINE COST ANALYSIS
050VARIABLE LIST;TCOST,X1 TO X9
060VAR LABELS;TCOST,ENGINE PRODUCTION COST/
070;X1,FAN/
080;X2,COMPRESSOR/
090;X3,COMBUSTOR/
100;X4,HIGH PRESSURE TURBINE/
110;X5,LOW PRESSURE TURBINE/
120;X6,BEARINGS SEALS AND DRIVES/
130;X7,CONTROLS AND ACCESSORIES/
140;X8,FRAMES/
150;X9,AUGMENTOR AND NOZZLE/
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;DISK
180N OF CASES;6
190MISSING VALUES;X1,X5,X9(0)
200READ INPUT DATA
210PARTIAL CORR;TCOST WITH X5 BY X2 TO X8(1,2)
220OPTIONS;2,7
230STATISTICS;1
240FINISH
250$:DATA:08
260$:SELECTA:77A68/ENGINE4,R
270$ENDJOB
```

APPENDIX C

Program for Computing First and Second Order Partial Correlations of X9 with TCOST

```
010##S,R(SL) :,8,16;;,16
020$:IDENT:WP1191,AFIT/SLG  GREENE & STARK
030$:SELECT:SPSS/SPSS
040RUN NAME;ENGINE COST ANALYSIS
050VARIABLE LIST;TCOST,X1 TO X9
060VAR LABELS;TCOST,ENGINE PRODUCTION COST/
070;X1,FAN/
080;X2,COMPRESSOR/
090;X3,COMBUSTOR/
100;X4,HIGH PRESSURE TURBINE/
110;X5,LOW PRESSURE TURBINE/
120;X6,BEARINGS SEALS AND DRIVES/
130;X7,CONTROLS AND ACCESSORIES/
140;X8,FRAMES/
150;X9,AUGMENTOR AND NOZZLE/
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;DISK
180N OF CASES;5
190MISSING VALUES;X1,X5,X9(0)
200READ INPUT DATA
210PARTIAL CORR;TCOST WITH X9 BY X2 TO X4,X6 TO X8(1,2)
220OPTIONS;2,7
230STATISTICS;1
240FINISH
250$:DATA:08
260$:SELECTA:77A68/ENGINE3,R
270$:ENDJOB
```

SELECTED BIBLIOGRAPHY

A. REFERENCES CITED

1. Baker, Bruce N. "Improving Cost Estimating and Analysis in DOD and NASA." Unpublished doctorial dissertation, School of Government and Business Administration, George Washington University, Washington, D.C., 1972.

2. Barga, Michael A. Project Engineer, Air Force Aero Propulsion Laboratory (AFAPL), Turbine Engine Division, Turbine Propulsion Branch, Wright-Patterson AFB OH. Personal interviews conducted intermittently from September 1976 to March 1977.

3. ________, and Captain Richard C. Poch, USAF. *Assessing Turbine Engine Costing Methodologies*. AFAPL-TBP-TM-75-3. Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, March 1975.

4. Bell, Kenneth B., Major, USAF. F-16 Financial Manager, Deputy for the F-16, Aeronautical Systems Division, Wright-Patterson AFB OH. Telephone interview. October 1976.

5. Birkler, John. Aerospace Engineer, Propulsion Branch, Air Vehicle Technology Department, Naval Air Development Center, Warminster, Pennsylvania. Telephone interview. March 1977.

6. Chase, Douglas C. Financial Specialist, Financial Management Group, Program Control Division, Deputy for International Fighter, Aeronautical Systems Division, Wright-Patterson AFB OH. Personal and telephone interviews conducted intermittently from August to November 1976.

7. Cimini, Libero. Manager, Turbojet Measurements, Aircraft Engine Group, General Electric Corporation, Lynn, Massachusetts. Personal and telephone interviews conducted intermittently November 1976.

8. Clark, Charles T., and Lawrence L. Schkade. *Statistical Analysis for Administrative Decisions*. 2d ed. Cincinnati: South-Western Publishing Company, 1974.

9. Deutsch, Stuart Jay, and John T. Berry. Final Report for Task 7 Under AFAPL SIP Program. Atlanta, Georgia: School of Industrial and Systems Engineering, Georgia Institute of Technology, January 1975.

10. Doyle, John. Contract Price Analysis Section, Air Force Plant Representatives Office, Detroit Diesel Allison, Indianapolis, Indiana. Telephone interview. January 1977.

11. Drake, Dr. John W., Mostata R. Reda, and James J. Allen, Jr. Feasibility Study of Initial Aircraft Propulsion Subsystem Integration Cost Model, Phase I. AFAPL-TR-75-88, Part I. Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, October 1975.

12. ________. Phase II of Feasibility Study of Initial Aircraft Propulsion Subsystem Integration Cost Model. AFAPL-TR-75-88, Part II. Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, October 1975.

13. Executive Office of the President, Office of Management and Budget. "Major System Acquisitions." Circular No. A-109. Washington, D.C., April 5, 1976.

14. General Electric Corporation. Report of Cost/Schedule Control System Demonstration Contract F33657-71-C-0762 Production Phase. Section I. General Electric Corporation, Aircraft Engine Group, Lynn, Massachusetts, March 1972.

15. Gibson, John D. S. Chief, Life Cycle Cost Office, Comptroller, Aeronautical Systems Division, Wright-Patterson AFB OH. Personal and telephone interviews. August 1976.

16. Greene, Kenneth F., Jr. Mathematician, Cost Analysis Data Center, Comptroller, Aeronautical Systems Division, Wright-Patterson AFB OH. Personal interview. September 1976.

17. Kendall, Maurice G., and Alan Stuart. The Advanced Theory of Statistics. 2d ed., Vol. 2. New York: Hafner Publishing Company, 1967.

18. Large, J. P. *Estimating Aircraft Turbine Engine Costs.* RM-6384/1-PR. Santa Monica, California: The RAND Corporation, September 1970.

19. Lawrence, Frederick P., Captain, USAF. Instructor of Quantitative Methods, Department of Quantitative Studies (LSGQ), School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH. Lectures delivered October 15-16, 1976 and personal interviews conducted intermittently July 1976 to February 1977.

20. Loren, Robert E. Dayton Representative, Pratt and Whitney Aircraft Company, Dayton, Ohio. Personal interview. January 1977.

21. Mullineaux, Rodney W. J., Captain, USAF, and Michael A. Yanke, Captain, USAF. "A Proposed Methodology for the Estimation of Jet Engine Costs in the Early Phases of the Weapon System Acquisition Process." Unpublished master's thesis. SLSR 02-76A, AFIT/SL, Wright-Patterson AFB OH 1976.

22. Murchland, Richard C. Chief, Cost Estimating Division, Deputy for the A-10, Aeronautical Systems Division, Wright-Patterson AFB OH. Telephone interview. October 1976.

23. Nie, Norman H., and others. *Statistical Package for the Social Sciences.* 2d ed. New York: McGraw-Hill Book Company, 1970.

24. Panella, Robert F. Aerospace Engineer, Air Force Aero Propulsion Laboratory (AFAPL), Turbine Engine Division, Turbine Propulsion Branch, Wright-Patterson AFB OH. Personal interviews conducted intermittently from September 1976 to January 1977.

25. ________. "Engine Life Cycle Cost: A Laboratory View," *Journal of Aircraft*, Vol. 13, No. 2, February 1976, pp. 156-8.

26. Schild, Daniel. Chief, Cost Management Systems Division, Directorate of Cost Analysis, Comptroller, Aeronautical Systems Division, Wright-Patterson AFB OH. Personal and telephone interviews conducted intermittently from September to November 1976.

27. Shockley, Jackson C., Major, USAF. Deputy, Air Force Plant Representative, General Electric Corporation, Evondale, Ohio. Personal and telephone interviews conducted intermittently from September to November 1976.

28. Stalker, Kenneth W. Chief, Consultant to the Director, General Electric Laboratories, Aircraft Engine Group, General Electric Corporation, Evondale, Ohio. Personal and telephone interviews conducted intermittently from October 1976 to March 1977.

29. U.S. Air Force Systems Command. Summary Report on the Low Cost Manufacturing/Design Seminar, 22-24 May 1973. AFML-TM-LT-74-3. Air Force Materials Laboratory, Wright-Patterson AFB OH, 15 December 1973.

30. ________. Summary of Air Force/Industry Manufacturing Cost Reduction Study, 28 August - 1 September 1972. AFML-TM-LT-73-1. Air Force Materials Laboratory, Wright-Patterson AFB OH, January 1973.

31. U.S. Department of the Air Force. Headquarters, Aeronautical Systems Division (ASD), Advanced Engines and Special Projects Working Group. Letter, subject: Aircraft Engine Life Cycle Cost Methods Improvement Working Group, 28 April 1976.

32. ________. Life Cycle Costing. AFR 800-11. Washington, D.C., 3 August 1973.

33. U.S. General Accounting Office. The Process for Identifying and Establishing Requirements for Major Weapon Systems in the Department of Defense. B-163058. Washington, D.C., 23 October 1974.

34. Williford, Richard L., Captain, USAF. J85 Engine Program Manager, Deputy for Propulsion Systems, Aeronautical Systems Division, Wright-Patterson AFB OH. Personal interview. October 1976.

35. Wonnacott, Thomas H., and Ronald J. Wonnacott. Introductory Statistics. New York: John Wiley and Sons, Inc., 1969.

36. Zambo, Leslie J., Major, USAF. Instructor of Quantitative Methods, Department of Quantitative Studies (LSGQ), School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH. Personal interviews conducted intermittently February to March 1977.

B. RELATED SOURCES

Batchelder, C. A., and others. An Introduction to Equipment Cost Estimating. RM-6103-SA. Santa Monica, California: The RAND Corporation, December 1969.

Bond, Tom. "Price and Cost Proposals." North Hollywood, California: Western Periodicals Company, 1969.

Boren, H. E., Jr. A Computer Model for Estimating Development and Procurement Costs of Aircraft (DAPCA-III). R-1854-PR. Santa Monica, California: The RAND Corporation, March 1976.

Department of Defense. Armed Services Procurement Regulation Manual (ASPM No. 1). Washington, D.C.: Government Printing Office, September 1975.

Fiorello, Marco. Estimating Life-Cycle Costs: A Case Study of the A-7D. R-1518-PR. Santa Monica, California: The RAND Corporation, February 1975.

Fisher, G. H. A Discussion of Uncertainty in Cost Analysis (A Lecture for the AFSC Cost Analysis Course). RM-3071-PR. Santa Monica, California: The RAND Corporation, April 1962.

________. Cost Considerations in Systems Analysis. R-490-ASD. Santa Monica, California: The RAND Corporation, December 1970.

Large, J. P., Harry G. Campbell, and David Cates. Parametric Equations for Estimating Aircraft Airframe Costs. R-1693-1-PA&E. Santa Monica, California: The RAND Corporation, February 1976.

Levenson, G. S., and S. M. Barro. Cost-Estimating Relationships for Aircraft Airframes. RM-4845-PR. Santa Monica, California: The RAND Corporation, February 1966.

________. Cost-Estimating Relationships for Aircraft Airframes. R-761-PR. Santa Monica, California: The RAND Corporation, December 1971.

Nelson, J. R. Performance/Schedule/Cost Tradeoffs and Risk Analysis for the Acquisition of Aircraft Turbine Engines: Applications of the R-1288 PR Methodology. R-1781-PR. Santa Monica, California: The RAND Corporation, June 1975.

Neter, John, and William Wasserman. Applied Linear Statistical Models. Homewood, Illinois: Richard D. Irwin, Inc., 1974.

O'Brien, Patrick W., Captain, USAF. "Joint Generalized Least Squares Applied to Cost Estimation for Fighter Aircraft." Unpublished master's thesis, GSA/SM/74D-7, AFIT, School of Engineering, Wright-Patterson AFB OH. December 1974.

Ostwald, Phillip F. Cost Estimating for Engineering and Management. New Jersey: Prentice-Hall, Inc., 1974.

Perry, R. L., and others. System Acquisition Experience. RM-6072-PR. Santa Monica, California: The RAND Corporation, November 1969.

Shishko, Robert. Technological Change Through Product Improvement in Aircraft Turbine Engines. R-1061-PR. Santa Monica, California: The RAND Corporation, May 1973.

Watts, A. Frank. Aircraft Turbine Engines--Development and Procurement Cost. RM-4670-PR (Abridged). Santa Monica, California: The RAND Corporation, November 1965.